DIMENSIONAL CHANGES IN SHOT GUN BARRELS CAUSED BY THE FIRING OF HARD METAL PELLETS

by

C. DAYSON AND T. MALONEY

R. B. Whyte, Head
Fuels and Lubricants Section

D. C. MacPhail
Director

SUMMARY

This report describes progress to date on the development of a means of assessing the wear and deformation of shot gun barrels caused by the firing of non-toxic but relatively hard metal pellets. The results of an initial series of tests on hard metal pellets, some of which were coated with non-metallic anti-wear coatings, are also presented. These indicate that the enlargement of the bore of the barrel at the muzzle constriction (choke) was, in this case, primarily due to the "hammering out" action of the hard pellets, with the wear of the bore being a secondary effect. The pellet coatings tested proved to be ineffective as a means of preventing either form of damage.

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1.0 INTRODUCTION

This investigation was initiated at the request of the Canadian Wild Life Service because of their concern over the large number of game birds, in particular wild ducks, being lost because of lead poisoning. As a result of the increased popularity of hunting, it is estimated that approximately 6,000 tons of lead are deposited in the water-fowl habitat in Canada every year. It is not surprising therefore that many birds that probe the mud bottom for food and small stones which they deposit in their gizzards to emasticate the food, also pick up quantities of the lead pellets. When this occurs, the pellets are ground up along with the food and conveyed to the stomach, where the lead is attacked and dissolved by the digestive juices and thus enters the blood stream. When the pellets ingested are of sufficient quantity, or the period over which this goes on is long enough, the birds become paralyzed and eventually die by starvation.

The severity of the lead poisoning problem has been pointed out by Solman (Ref. 1) who has suggested that the yearly water-fowl loss incurred in this way may be as high as 1 million birds. With both Canada and the United States involved in high cost land acquisition programs in an attempt to conserve wild life, obtaining a solution to this problem is seen as just a part of a larger plan of conservation and resource protection. It is also thought that the large quantities of lead now being deposited could have a general adverse effect on the ecology of the wetlands; it is hoped, therefore, that a solution to the waterfowl poisoning problems might also alleviate some of these difficulties.

Various means of overcoming the lead poisoning problem have been suggested. These proposals include the use of pellets made from other common but non-toxic metals, the coating of lead pellets with an outer skin of a harder metal that would resist the pulverising action in the bird's gizzard, and the use of lead powder held together in a pelletised form by a water-soluble glue. In the latter case, it is intended that the pellets would revert to the powder when they fall into water, and so would not be ingested by the birds.

On the basis of toxicity testing and trial firings with various pellets of these types, it seems that the possibility of using iron or nickel pellets to replace lead offers the most promising means of solving the problem. These metals are dense enough to have acceptable ballistic characteristics, and at the same time cheap enough to be economically feasible. However, in their most common forms these metals are, of course, much harder than lead, and may even be as hard or harder than shotgun barrels. It is to be expected, therefore, that guns from which such shot is fired would be subject to appreciable internal barrel wear after firing only a relatively small number of rounds. This is the only major drawback to the possibility of replacing lead by such materials.

Studies of this aspect of the problem undertaken elsewhere (Ref. 2) have shown that this difficulty does arise in practice. Attempts have been made to overcome it by making use of soft forms of the metals in question. However, because reports on these studies are not generally available and there are so many confusing and contradictory opinions on the matter, it was felt that an independent enquiry was required.

Accordingly this investigation was instigated with the aim of assessing the amount of barrel wear that occurs with these non-toxic, but harder types of shot, with the hope of developing a shot material that gives rise to acceptably small, or no damage to the weapon while satisfying the toxicity, ballistics, and cost requirements.

2.0 EXPERIMENTAL METHOD

The most suitable type of experiment for this purpose is one where the wear is measured in actual shotguns from which pellets made from the candidate materials are fired. Although it may have been possible to carry out a high speed wear experiment in some form of wear-testing machine, it was thought that this was not the wisest course of action. As a result of a lack of knowledge regarding the wear-controlling parameters, e.g. normal load and type of motion between pellets and barrel wall, it was felt that the interpretation of the results of such experiments would be open to criticism.

In the first series of tests reported here, experiments have been carried out with relatively hard pellets made from materials that were not selected as ones likely to replace lead. They were tested in this instance because they were readily available at low cost, and would provide a means of assessing the effectiveness of the experimental methods being used. It was also seen as an opportunity of partially determining the effectiveness of coating pellets with plastic films and other solid lubricating materials as a means of reducing barrel wear.

The technique used in these experiments involved the measurement of gun barrel diameters and of other characteristics that enable a better assessment of the barrel damage to be made, before and after the firing of a given number of rounds of the test shot. In this report, values of the surface roughness of the barrel bore at the muzzle and of the concentration of a sample of lead shot at the target, are presented to substantiate the findings obtained from the barrel size measurements.

Cheap single-barrel "full choke" 12-bore shotguns were used. Guns such as these were chosen for two reasons: the barrels were cheap and easily replaced, and the steel from which they are made is of the lowest possible quality for this purpose, so the barrels would be softer and more subject to wear than other more expensive guns. Fully choked guns, i.e., those with barrels having the largest muzzle constriction used in practice, were utilised as it was expected that the greatest degree of muzzle wear would take place with such barrels.

2.1 Barrel Sizing

Barrels were measured to obtain the inside and outside diameters in vertical and horizontal planes (with reference to the usual firing position) at specified stations along the barrels. Standard inspection techniques and equipment were used in making these measurements to an accuracy of approximately 10^{-4} inches.

The internal diameter was measured at a greater number of stations than the external one, since the primary interest was with wear. The external diameter measurements were made because it had been learnt that changes in this dimension can take place near the muzzle as a result of the "hammering out" action of the pellets that may occur because of their impact with the muzzle choke.

2.2 Measurement of Bore Roughness

A plastic replica technique was used to assess the magnitude of the surface roughness of the gun barrel bore at a point approximately $\frac{1}{4}$-inch from the muzzle. The method involved softening one side of a small piece of 0.015-inch thick cellulose acetate sheet with acetone and pressing this against the bore with a matching piece of rubber. When the surface of the cellulose acetate had hardened, it was removed from the barrel and bonded by its untreated surface to a flat metal backing piece. Roughness traces and roughness ratings (centre line average) were then obtained in the usual way, using the Talysurf machine.

2.3 Shot Pattern Measurement

The degree of spreading of the train of shot that takes place after it has left the gun is of considerable interest to the hunter, since this effect controls the killing power of a shell. In view of this, it was felt that measurements of "the pattern" or the concentration of shot at a fixed distance from the gun would provide useful information with regard to two particular points: i) another means of assessing the barrel wear or deformation occurring with the shot to be tested, and ii) data that might be used to convince the hunter that a certain type of shot could replace lead without resulting in any deterioration of his weapon's effectiveness, or unacceptable changes in the concentration of the fired shot.

Several methods of estimating the shot concentration at a fixed distance from the gun were considered. Some measurements of this factor have been made elsewhere (Ref. 2) by shooting at sheets of paper and then counting the number of holes inside a circle of fixed diameter that is positioned to contain what is estimated to be the greatest possible number of holes. This procedure is tedious and subject to inaccuracies as a result of errors in the positioning of the circle, with the result that the average of a large number of patterns (eg. 25) is required.

The use of sheets of paper as a means of obtaining and storing pattern information could not be readily improved upon, but it was felt that a more refined technique of measuring the concentration of holes could be employed. Optical techniques seemed to offer the most feasible means of upgrading this part of the method. The possibility of using a fully collimated beam of light whose diameter would be that of the chosen circle size was investigated. In such a device a second lens system would be used to focus the light onto a receiver, the signal from which would be proportional to the number of holes in the paper pattern that would be placed across the parallel part of the light beam. To obtain a discreet relationship between the number of pellet holes in a circle of given diameter and the receiver signal it is essential that the light flux be uniform to within small limits across the width of the parallel part of the beam. Unfortunately this requirement makes the cost of such a large-stage instrument very high.

There is another type of optical instrument that is more suited to these requirements - one that utilises diffuse light. The basis for the use of diffuse light as a means of area measurement has been described elsewhere (Ref. 3), and an instrument designed on this principle has been developed for measuring the area of leaves. An almost identical "photo-electric planimeter" has been built to carry out the shot pattern concentration measurements. The planimeter illustrated in Figure 1 consists of a wooden cabinet divided into two cube-shaped sections, one above the other. The lower cube, with its eight fluorescent lights, A, mounted around the edges of its upper surface and its white matt finish, acts as an integrating diffuse light source, providing a uniform illumination of the 18-inch square diffusing window, B, separating the two parts of the planimeter. The upper cube was lined internally with black velvet to prevent any reflection from its internal surfaces to the four photo-electric cells, C, mounted at specified symmetrical positions near the upper corner of the cube. The four photo-electric cells were connected in series to a vacuum tube voltmeter having the required sensitivity.

The aperture of the planimeter was cut down to a circular area 10 inches in diameter, positioned centrally in the cabinet by inserting a black paper mask immediately above the diffusing plate. In the studies mentioned earlier, a 30-inch diameter circle was used, but with the reduced distance between the gun and the target used in this investigation, the 10-inch circle was found to be more suitable and convenient.

The device was calibrated by plotting the voltmeter reading against the number of holes from which light fell on the sensors, for a number of paper patterns covering the whole range of shot concentrations (Fig. 2). The paper through which the shot was fired was an opaque black type, 0.001 inch thick. Five such patterns were made before and after the firing of each batch of shells containing a given type of test shot, using standard loads of lead pellets. The sheets of paper were mounted immediately in front of the target 23 yards from the muzzle of the gun. The required planimeter reading for each pattern was obtained by moving the pattern backwards and forwards and from side to side until a maximum voltmeter reading was obtained. In this position the pattern was situated so that the greatest number of pellet holes fell within the 10-inch diameter aperture of the planimeter, obviating the need to estimate the relative positions the aperture and the pattern should take. The voltmeter reading with the paper pattern in this position was then recorded so that the number of shot holes inside the 10-inch circle could subsequently be estimated. A ratio called the 'pattern percentage' was obtained by dividing the number of shot holes by the average number of pellets contained in the cartridges. Finally, the average pattern percentage was calculated from five paper patterns produced in each instance.

2.4 Firing Range and Shotgun Mount

The test firings were carried out partly in a 25-yard long indoor rifle range, and partly out of doors. Because of the restricted length of the indoor range, which was used during the winter months, it was necessary to establish a distance standard of 23 yards between the muzzle and the target.

A facility was also provided to collect the test shot after firing from the guns. This consisted of a large number of Mylar sheets suspended vertically from horizontal rods positioned at right-angles to the direction in which the shots were fired. The sheets were mounted immediately in front of the target, above a steel tray from which the shot could be collected after it had been brought to rest, without damage by the mylar sheets.

To reduce the strain on the person firing, the guns were not aimed from the shoulder, but fixed in a recoiling mount. In this way a gun could be aimed at the target initially and the shells then fired with some rapidity.

3.0 PELLETS TESTED

Seven types of pellets were fired in this first series of tests. Details of the types of shot and coatings applied to them, and information regarding their loading into shells, is given in Table 1. Barrel pressure and muzzle velocity measurements are also given. These were carried out in the usual way to ascertain that the weights of shot, amounts of powder, and wad pressures used during the hand-loading operation, were suitable. The measured pressures and velocities for the shells loaded with uncoated nickel shot were below the operating range of the measuring equipment. Nevertheless, the amount of wear and deformation that took place with this shot was still significant enough to enable conclusions to be drawn as to the suitability of these particular pellets for general usage in shotguns. Shells loaded with coated nickel pellets, in which greater weights of shot were used, caused velocities and pressure to be in the range that is usually acceptable, and typical of shells containing lead pellets.

4.0 TEST PROCEDURE

As there was no definite information to indicate how many rounds of the test shot should be fired before the barrels were remeasured and their patterns reassessed, these operations were first carried out after only 25 rounds had been fired. Although it was found that the barrel damage and wear was appreciable with the hard metal pellets after this small number of rounds had been fired, the changes in dimensions were still only slightly greater than the repeatability of the measurements. Accordingly, another 75 rounds of the test shots were fired from each gun, after which the barrels were again remeasured.

5.0 RESULTS

In order to verify the repeatability of the barrel diameter measurements, one barrel was measured a second time. The differences between the average internal and external diameters calculated from these two sets of measurements are given in Figure 3 for those stations near the muzzle where the greatest amount of wear and surface damage occurred. The errors involved were somewhat greater than the 10^{-4} inches to which the measuring equipment is capable of working. Apparently this was due to errors resulting from a lack of accuracy in the angular location of the barrels during the mensuration. The location was carried out visually with respect to the small spherical sight located near the muzzle of the gun. That such errors could arise in this way can be appreciated from Figure 4, which is a roundness trace of the outside of one of the barrels a $\frac{1}{4}$ inch from the muzzle. An error of 5° in the angular location of this particular barrel at this location could have given variation in the diameter reading of as much as 0.001 inch. The average bore diameter at the muzzle of a barrel measured before and after the firing of 25 rounds of carbonyl nickel shot, are presented in Figure 5. The presence of the muzzle constriction is readily apparent, and the increase in the bore dimensions that occurred in this region during the firing is noticeable. The corresponding changes in the outside diameters, albeit at a smaller number of stations, are given in Figure 6. These results may be expressed in a more meaningful way. If, as mentioned earlier, it is assumed that the deterioration of the barrel can result from internal wear and/or expansion, then it can be seen from Figure 7 that at any station (D_2-D_1) the difference in the mean outside diameters, before and after the test firings, must be a measure of the change in the barrel's dimensions because of the latter effect. Also (d_2-D_1 + D_1-d_1), where d_1 and d_2 are the bore diameters before and after firing, is a measure of the change of internal diameter caused by wear. Both these parameters are plotted in Figure 8. Since both parameters contain the external diameters D_2 and D_1, their values could only be established at stations where the external diameter was measured.

It appears from Figure 8 that the changes in the barrel dimensions evident in Figures 5 and 6 were due partly to barrel expansion and partly to the wear occurring in the bore. However, the scatter in these results, which are typical of those obtained with the other hard metal pellets, is plainly of the same order as the changes in diameter due to both these effects. This is shown by making a comparison with the curves of typical error; Fig. 3. Therefore, it was decided that it was necessary to fire a greater number of rounds of the test shot from each barrel. The results of measurements obtained after a further 75 rounds had been fired are given in Figures 9 to 29 for all the types of shot tested. The results for Teflon-coated shot, Figures 27 to 29, refer to measurements made after 25 rounds; the barrel split during the second series of firings as a result of metallurgical defects in the steel (Ref. 4).

The graphs of barrel bore diameter show that the size of the constriction varied considerably from barrel to barrel, despite the fact that, nominally, they were all fully choked. This variation did not give rise to any difficulty in the interpretation of the results, since it was found that the magnitude of the constriction was not of primary importance in barrel damage.

Figures 9 to 11 show the measured changes in the dimensions of a barrel from which 125 rounds of lead shot were fired. Clearly the amount of wear or surface damage was immeasurable; the changes owing to wear and expansion of the barrel (Fig. 11) are of approximately the same magnitude as the measurement errors. This result was expected since it is found that, in practice, many thousands of rounds can be fired without any barrel damage becoming apparent. Roughness measurement results are given in Table 2; the small but significant increase in the roughness in this case was probably due to a thin layer of lead that seemed to have been deposited on the bore.

Significantly different results were obtained with the other, harder metal pellets tested. Measurements of the barrel from which 100 rounds of uncoated carbonyl nickel shot were fired (Fig. 12 to 14) show that considerable changes in the inside and outside diameters occurred. Wear damage to the inside of the bore was apparent after only a few rounds of shot had been fired. The severity of the damage is apparent from Figures 32 and 33, which are photographs of the bore (at the muzzle), taken initially and after 25 rounds of the nickel shot had been fired. The large increases in the roughness of the bore noted in Table 2 also reflect the severity of the wear process. The degree of surface damage occurring can be better appreciated from the roughness traces of Figure 31, obtained from the plastic replicas made before and after the firing of the test shot. Despite the seriousness of this effect, it can be seen from Figure 14 that greater dimensional changes occurred as a result of the hammering-out action of the train of pellets on the choked muzzle. This is not surprising when it is realized that these nickel pellets were of a hardness in the range 300 - 460 V.D.H. compared with the hardness of the barrel, which was only 210 - 220 V.D.H. The barrel wear, although it is obviously an important effect with these hard pellets, does not cause dimensional changes significantly greater than the measurement errors. However, the presence of negative wear suggested in Figure 14 is supported by visual evidence of a piling-up action at the muzzle. It seems that the ploughing action of the pellets against the bore could gradually be moving small quantities of the barrel material towards the muzzle, where a burr was formed.

Results similar to those obtained with nickel were found with all the other types of pellets tested (Fig. 15 to 29). The comparatively large changes in dimensions at the muzzle due to the expansion of the barrel, in relation to the changes due to wear, are clearly evident in each case. Dimensional changes in the parallel sections of the barrel were always negligibly small, although the bores were severely scored along their whole length and pitted near the breach.

To emphasize the relative magnitudes of the wear and barrel expansion that occurred, Table 3 shows the maximum changes in diameter due to these two effects. The greater increases in diameter due to expansion were from 3 to 30 times the corresponding changes due to wear. Also, it is apparent that the expansion with the steel BB shot was of a similar magnitude to that caused by the nickel shot, despite the reduced muzzle velocity at which the latter was fired.

The tests with the coated nickel pellets showed that none of the coatings investigated were effective as a means of reducing the hammering-out action occurring with these hard pellets. This is not surprising in view of the small thicknesses of the coatings applied to the pellets, the thickest being the epoxy resin coating, which was only several thousandths of an inch deep. Had the uncoated nickel pellets been fired at the same speed as the coated ones, some benefit might have been apparent in this respect; however, the large expansions of the barrels from which the coated shot was fired mean that such pellets are unsuitable in any case. The coatings do seem to give some reduction in the change in dimensions because of wear, but bearing in mind our reservations with regard to the wear values (see typical error in Table 3), this cannot be too certain. Furthermore, examinations of the coated shot after it had been fired from the guns seemed to suggest that the coatings were easily worn through to expose the bare metal. At points on the pellets fairly large flats existed, presumably formed as result of the rubbing action against the barrel. Thus. conditions were sufficiently extreme at the rubbing interface for the removal of fairly large quantities of this hard material. It is not surprising, therefore, that the coatings should be found to be incapable of protecting the surfaces.

The ineffectiveness of the coatings in preventing barrel wear is also illustrated by their inability to reduce the increase in the surface roughness of the bore that takes place when hard pellets such as these are used (see Table 2). The apparent decrease in the roughness of the bore of the barrel through which the steel BB shot was fired cannot be satisfactorily explained. Visual examination of the surface of the bores showed them to be scored and worn just as with the uncoated nickel pellets. This is further evidence to suggest that the coatings were ineffective in reducing wear.

Results of the pattern measuring tests are given in Figure 31, which shows the pattern percentage plotted against the number of rounds of the test shot fired for each type of shot tested. As would be expected, the results generally indicate a reduction in the concentration of the train of shot as the choke of the gun was reduced because of the expansion at the muzzle. Exceptions were the cases of Teflon and epoxy resin coated nickel shot, where the measured concentration did not vary. Lead gave an increased concentration after 125 rounds had been fired; however, this figure was obtained as an average of only two patterns.

6.0 CONCLUSIONS

Despite the lack of sufficient accuracy in the technique used in measuring the gun barrels, the results of the present study bring out several important points. Firstly, when hard metal pellets (harder than the gun barrels) are used to replace the lead pellets usually utilised in shotgun shells, it is the expansion of the barrel near the muzzle, i.e. the reduction in the required choking effect by hammering out, that is the major reason why such pellets give unsatisfactory results. In this case the wear is a secondary effect, although probably not a negligible one as it is with lead pellets. For instance, in the chokeless guns used in some sports, the expansion at the muzzle might not be important and the gun would probably simply wear out, becoming an unsatisfactory weapon or one that is unsafe.

It has also been shown that, with the hard pellets tested, the use of coatings on the pellets is not an effective way of reducing either the expansion or the wear of the barrels. Perhaps if thicker coatings were used, a wear-reducing effect might be obtained along with a cushioning action, which might prevent the expansion as well. However, such coatings would probably have to be at least 10 thousandths of an inch thick, and since the pellets are only of the order of one-tenth of an inch diameter, the coating would occupy an appreciable part of the total volume of the pellet, giving rise to a reduced mean density. Although there are arguments for reducing the density of shotgun pellets as a means of changing their ballistical characteristics, the density of such pellets would be considerably lower than the density of iron, which itself is considerably less than that of lead.

7.0 FURTHER STUDIES

In view of these results it seems that the most promising area of endeavour would be to examine the possibilities of using softer forms of the relatively cheap metals such as iron and nickel. Shot manufactured from pure forms of these metals, which are capable of being annealed to hardnesses considerably lower than that of any gun barrel, are now being processed. These pellets, however, have been made by the expensive method of drawing the metal into wire, and cold heading into pellets. It is also proposed to test shot made from pure iron and nickel powders by a process of agglomeration and sintering. A form of soft iron pellets developed by a private firm will also be tested.

Before this second generation of tests is carried out, it is intended that the techniques of measuring the barrels should be upgraded so that the changes in the bore diameters resulting from the wear process may also be assessed more accurately. This refinement is very necessary because the amounts of wear occurring with the softer shot will probably be even smaller than those occurring here. Attempts will also be made to improve the method of measuring pattern changes during the process of wear or expansion of the barrels. A gun mount for holding the test guns while large numbers of rounds are fired has been manufactured, as more rounds will probably have to be fired in future tests on the softer metals.

8.0 REFERENCES

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TABLE 1

DETAILS OF SHOT TYPE, SHELL LOADS AND FIRING CHARACTERISTICS

Shot Material	Type of Coating	Size of Shot	Weight of Shot Load Oz	Amount of "Green Dot" Powder Grains	Barrel Pressure psi	Muzzle Velocity Ft/sec
Lead	-	4	1-1/8	23	5000	1000
Steel BB	-	-	1	23	4400	1100
Carbonyl Nickel	-	5 or smaller	1	23	*	*
Carbonyl Nickel	Epoxy Resin	5 or smaller	1-1/8	23	4250	1000
Carbonyl Nickel	Teflon	5 or smaller	1-1/8	23	6200	1215
Carbonyl Nickel	Resin Bonded MoS_2	5 or smaller	1-1/8	23	6500	1025
Carbonyl Nickel	Burnished MoS_2 Powder	5 or smaller	1-1/8	23	5600	1065

* Below operating range of measuring equipment

TABLE 2

SURFACE ROUGHNESS OF BORE APPROXIMATELY
$\frac{1}{4}$ INCH FROM MUZZLE

Shot Material	Type of Coating	Surface Roughness μin C L A		
		Initial	After 25 Rounds	After 100 Rounds
Lead	-	35 - 48	-	50 - 55 *
Steel BB	-	35 - 48	90	48
Carbonyl Nickel	-	35 - 48	50	113
Carbonyl Nickel	Epoxy Resin	35 - 48	58	145
Carbonyl Nickel	Teflon	35 - 48	79	140
Carbonyl Nickel	Resin Bonded MoS_2	35 - 48	83	93
Carbonyl Nickel	Burnished MoS_2 Powder	35 - 48	97	148

* After 125 rounds

TABLE 3

MAXIMUM INCREASE IN BORE OWING TO
WEAR AND EXPANSION

Shot Material	Type of Coating	Maximum Diametral Wear at Choke, Inches		Maximum Diametral Expansion at Choke, Inches	
		After 25 Rounds	After 100 Rounds	After 25 Rounds	After 100 Rounds
Lead	-	-	0.0007	-	0.0011
Steel BB	-	0.0002	0.0006	0.0029	0.0066
Carbonyl Nickel	-	0.0016	0.0014	0.0011	0.0048
Carbonyl Nickel	Epoxy Resin	0.0008	0.0019	0.0018	0.0062
Carbonyl Nickel	Teflon	0.0009	*	0.0009	*
Carbonyl Nickel	Resin Bonded MoS_2	0.0002	0.0008	0.0020	0.0041
Carbonyl Nickel	Burnished MoS_2 Powder	0.0001	0.0002	0.0018	0.0064
Typical Error		0.0006		0.0006	

* Barrel failed prior to completion of test series

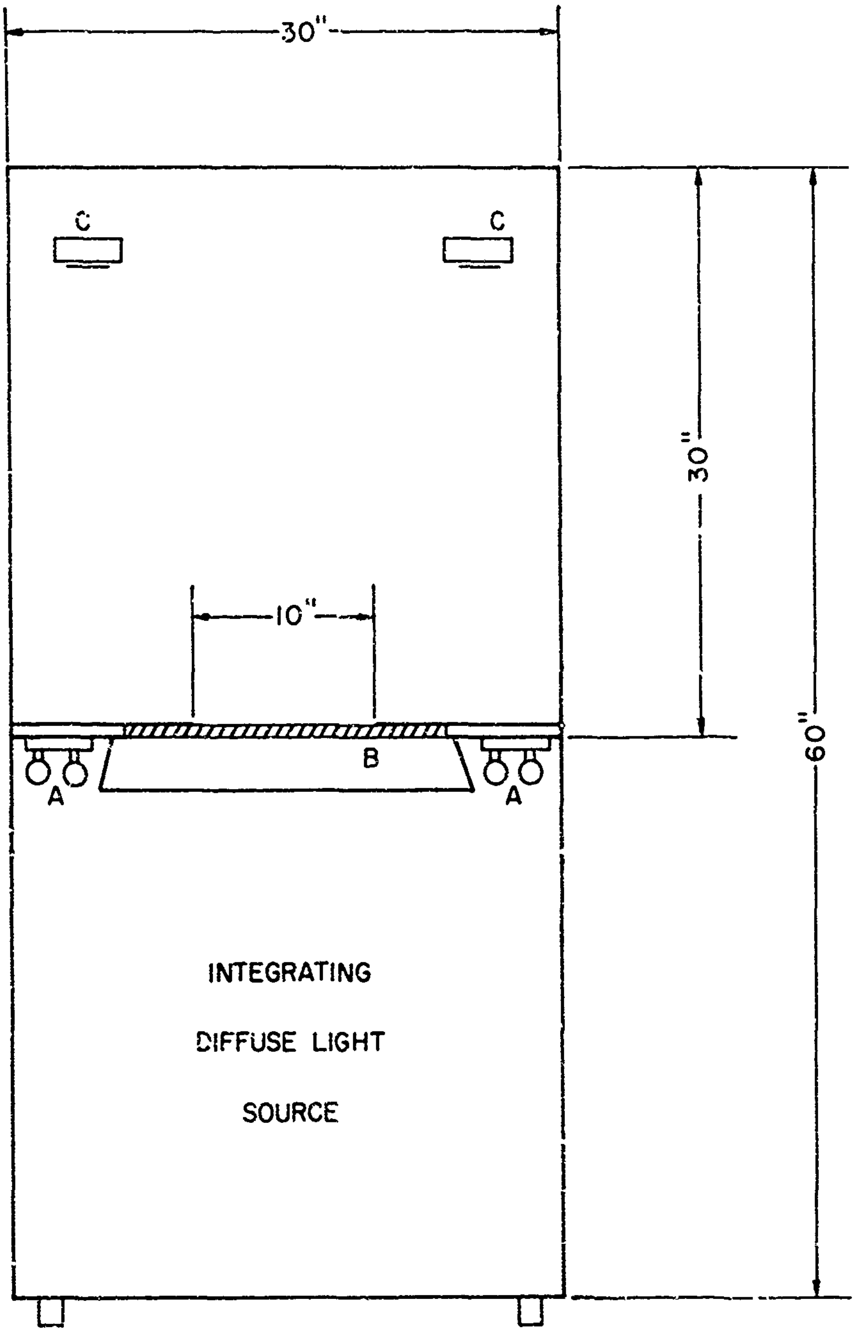

FIG. I: DIFFUSE LIGHT PHOTO-ELECTRIC PLANIMETER USED FOR ASSESSING PATTERNED SHOT CONCENTRATIONS

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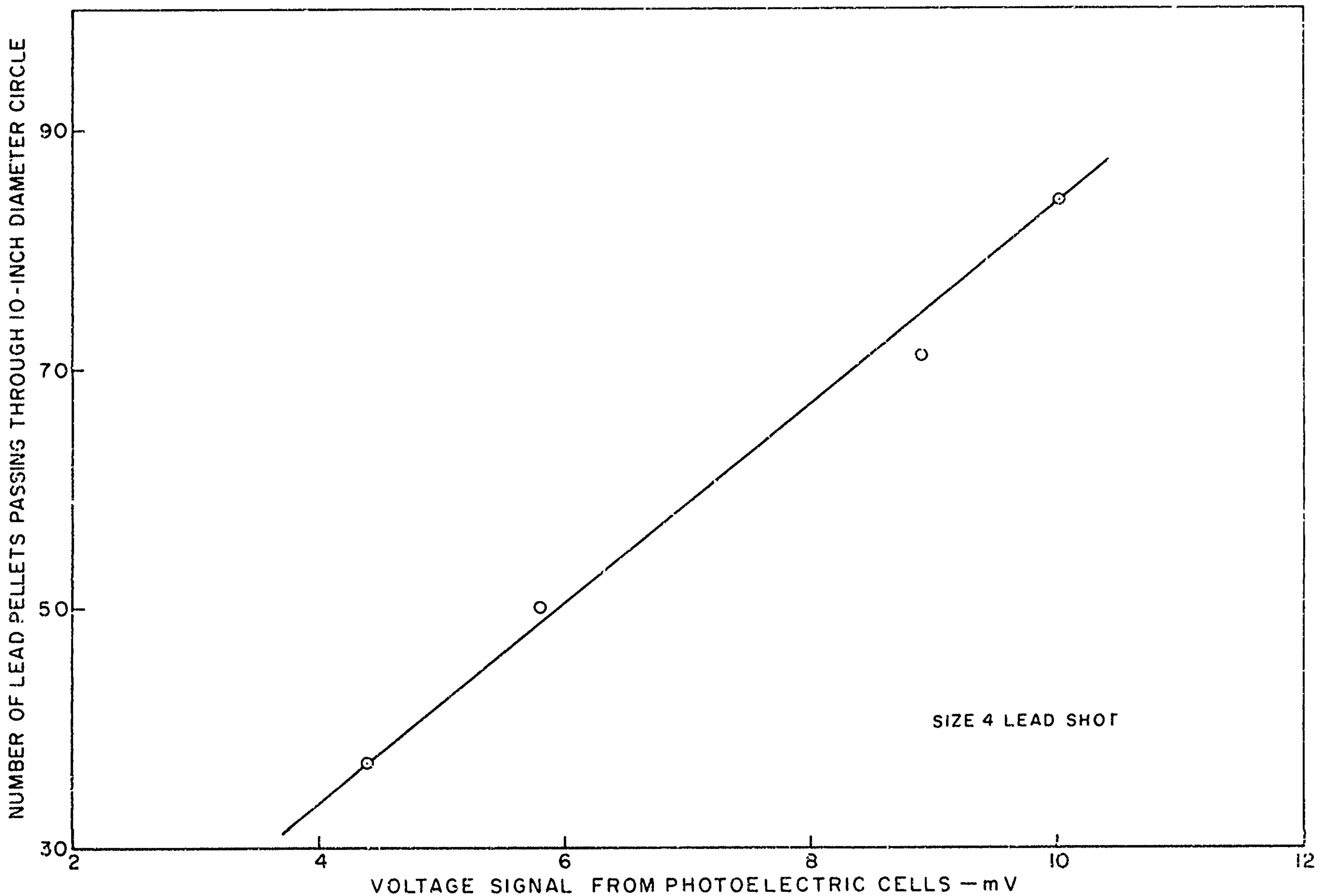


FIG.2: CALIBRATION OF PHOTO-ELECTRIC DEVICE USED TO RATE SHOT PATTERNS

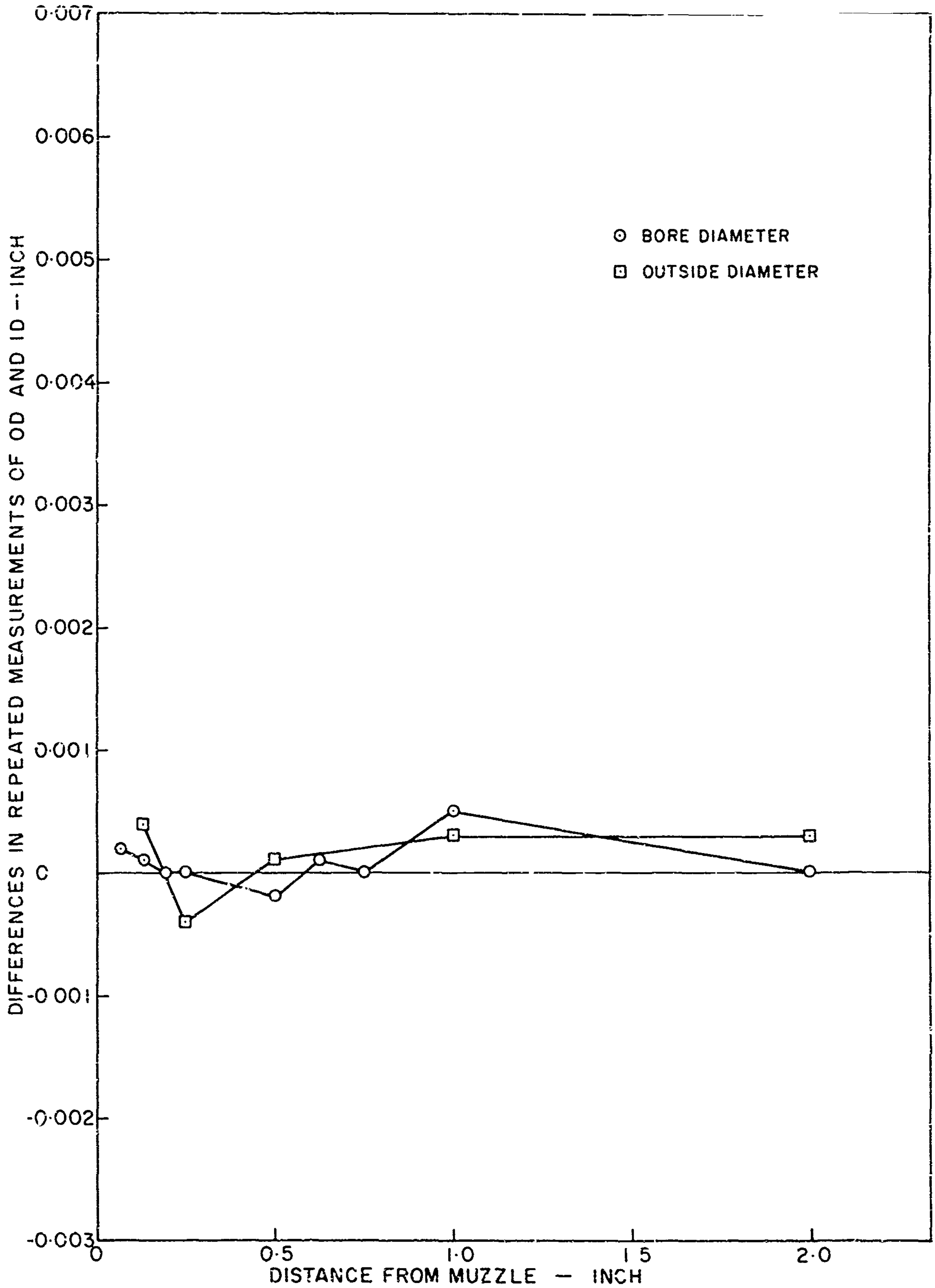


FIG.3: TYPICAL BARREL DIAMETER MEASUREMENT ERRORS

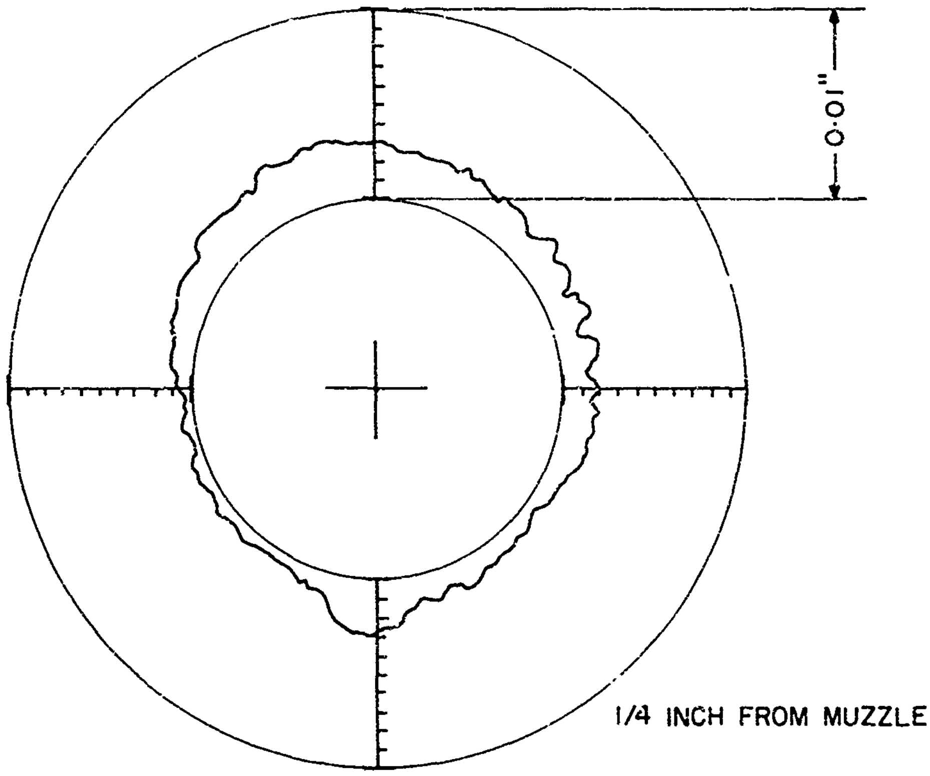


FIG. 4: TYPICAL ROUNDNESS TRACE AT OUTSIDE DIAMETER

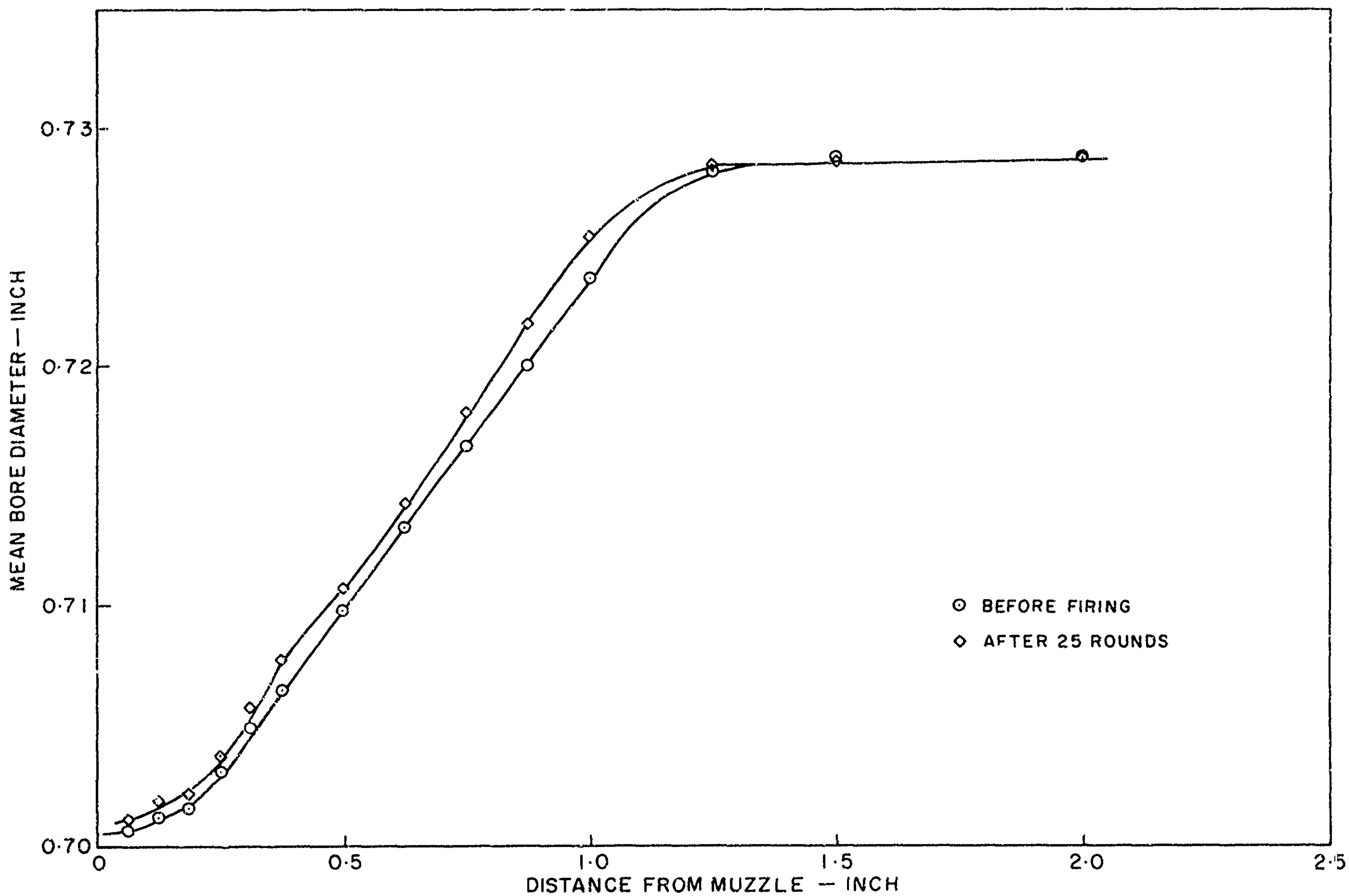


FIG.5: BORE DIAMETER AT MUZZLE, CARBONYL NICKEL SHOT

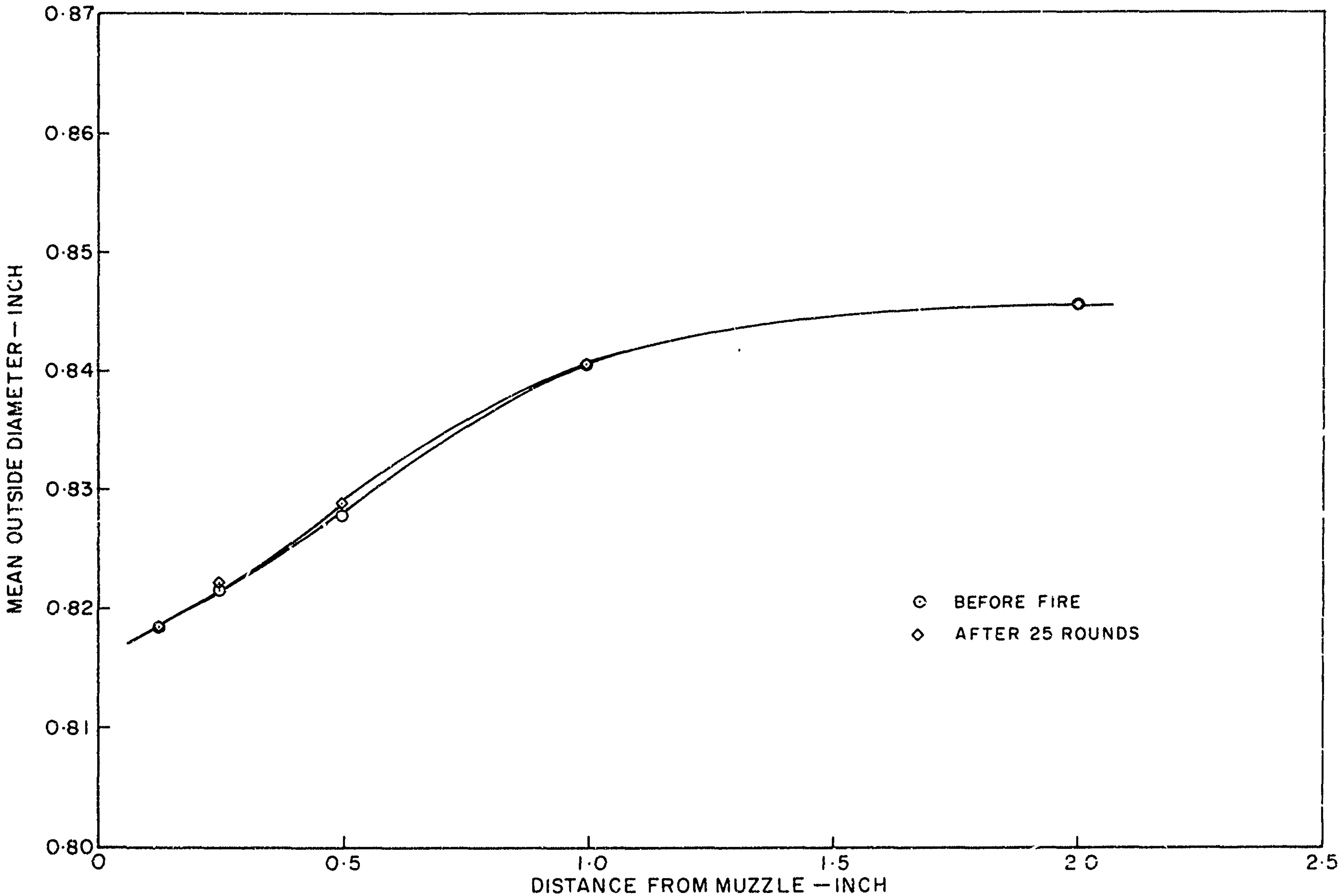
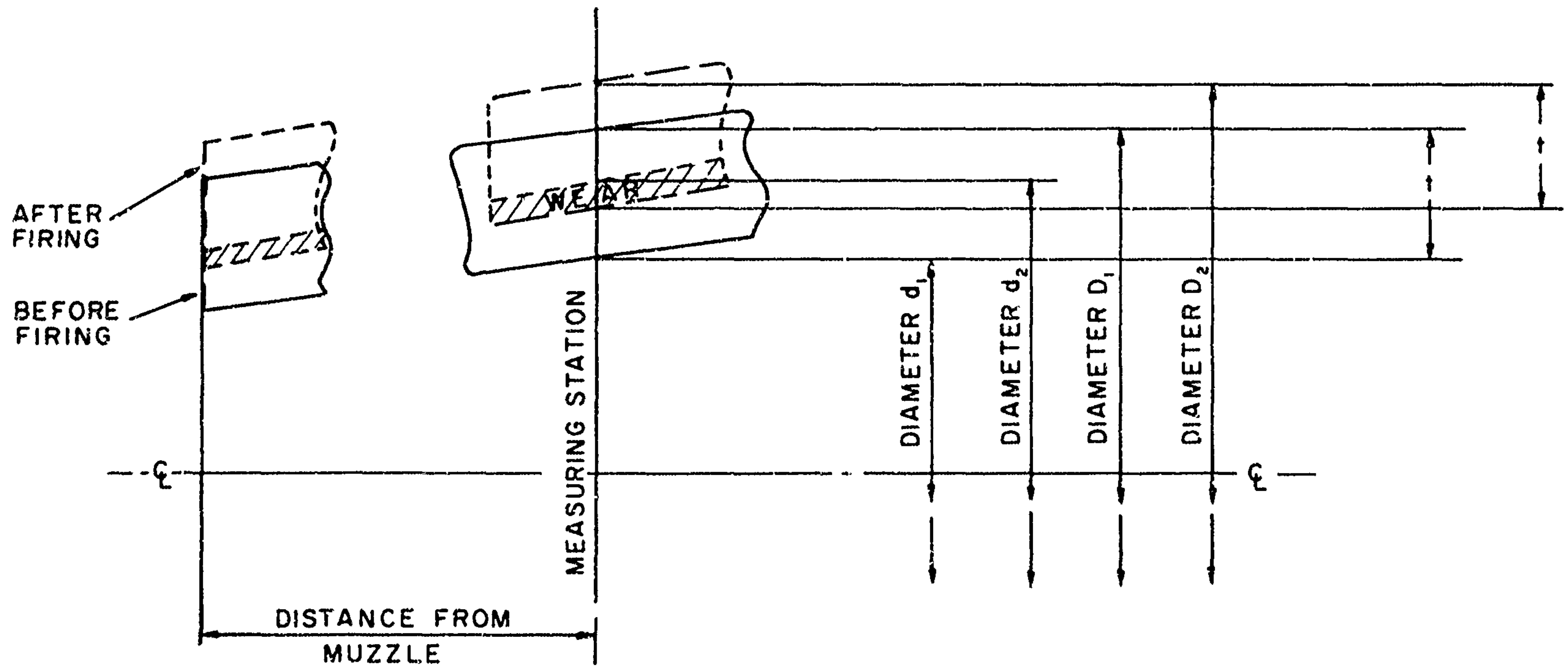


FIG.6: OUTSIDE DIAMETER AT MUZZLE, CARBONYL NICKEL SHOT



THICKNESS OF BARREL WALL = t

CHANGE IN BORE DIAMETER OWING TO WEAR $= d_2 - D_2 + D_1 - d_1$

CHANGE IN BORE DIAMETER OWING TO EXPANSION $= D_2 - D_1$

FIG.7: SKETCH SHOWING DIMENSIONS USED IN CALCULATING CHANGE IN BORE OWING TO WEAR AND EXPANSION

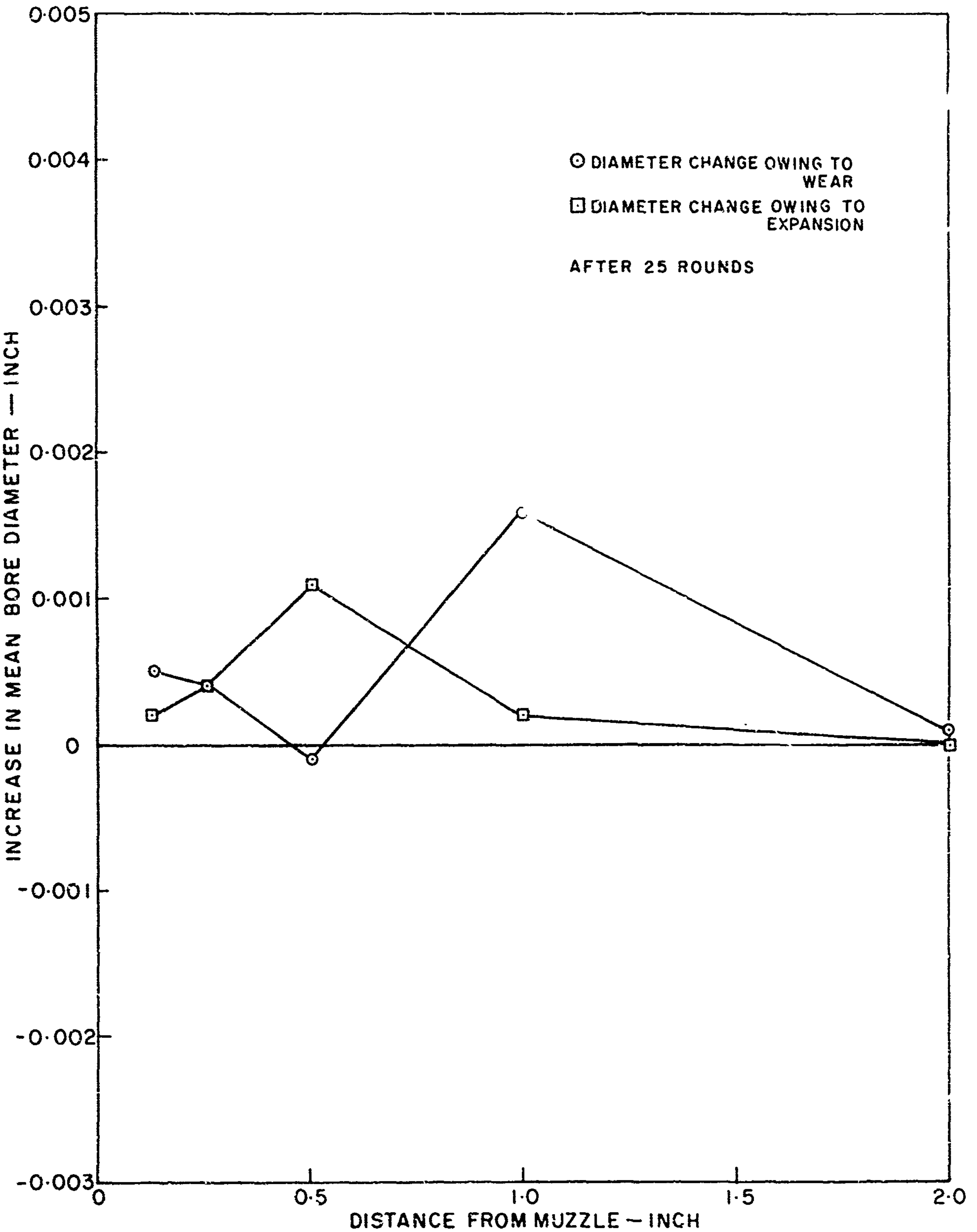


FIG. 8: CHANGES IN BORE DIAMETER OWING TO WEAR AND EXPANSION, CARBONYL NICKEL SHOT

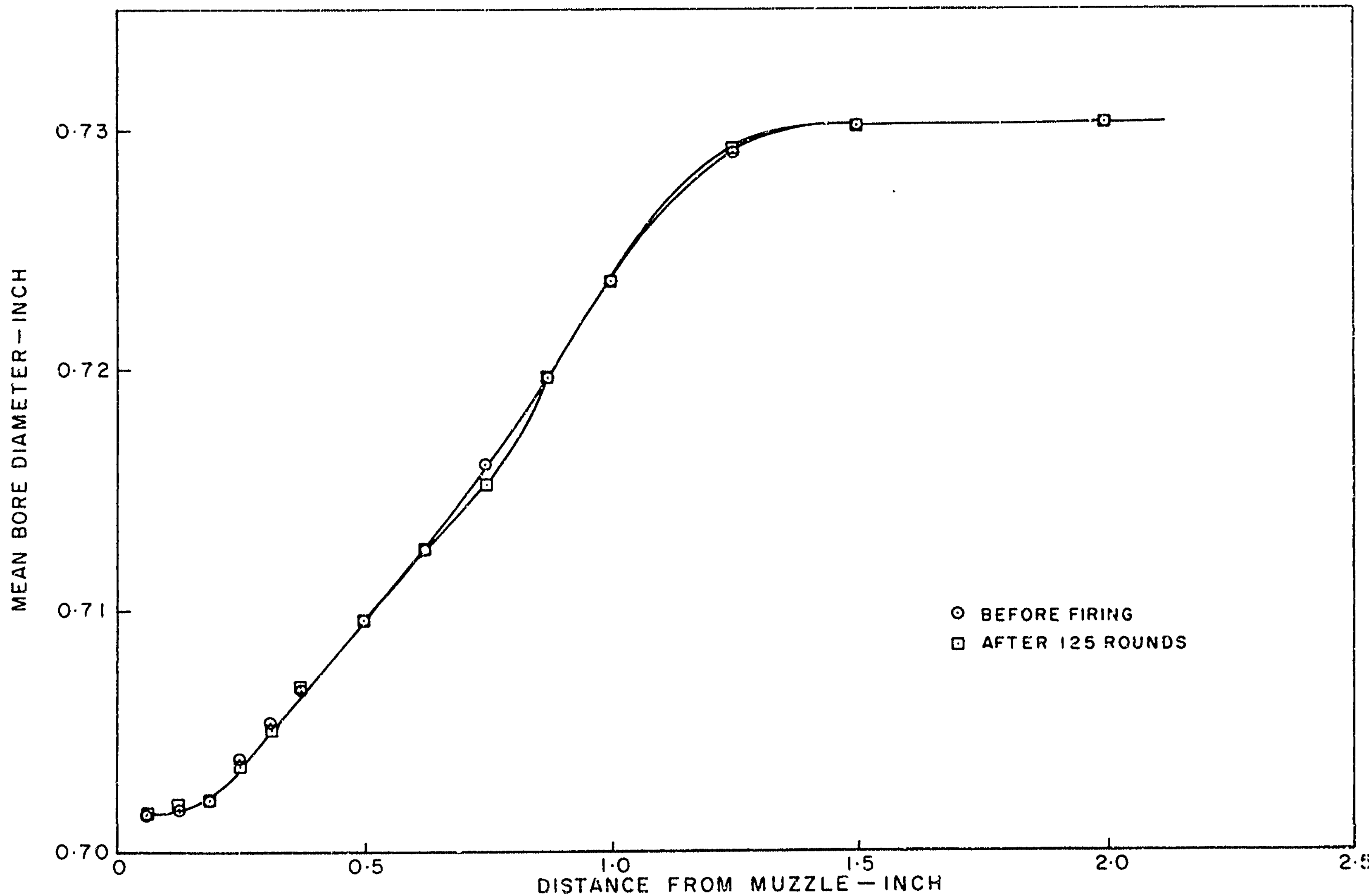


FIG. 9: BORE DIAMETER AT MUZZLE, LEAD SHOT

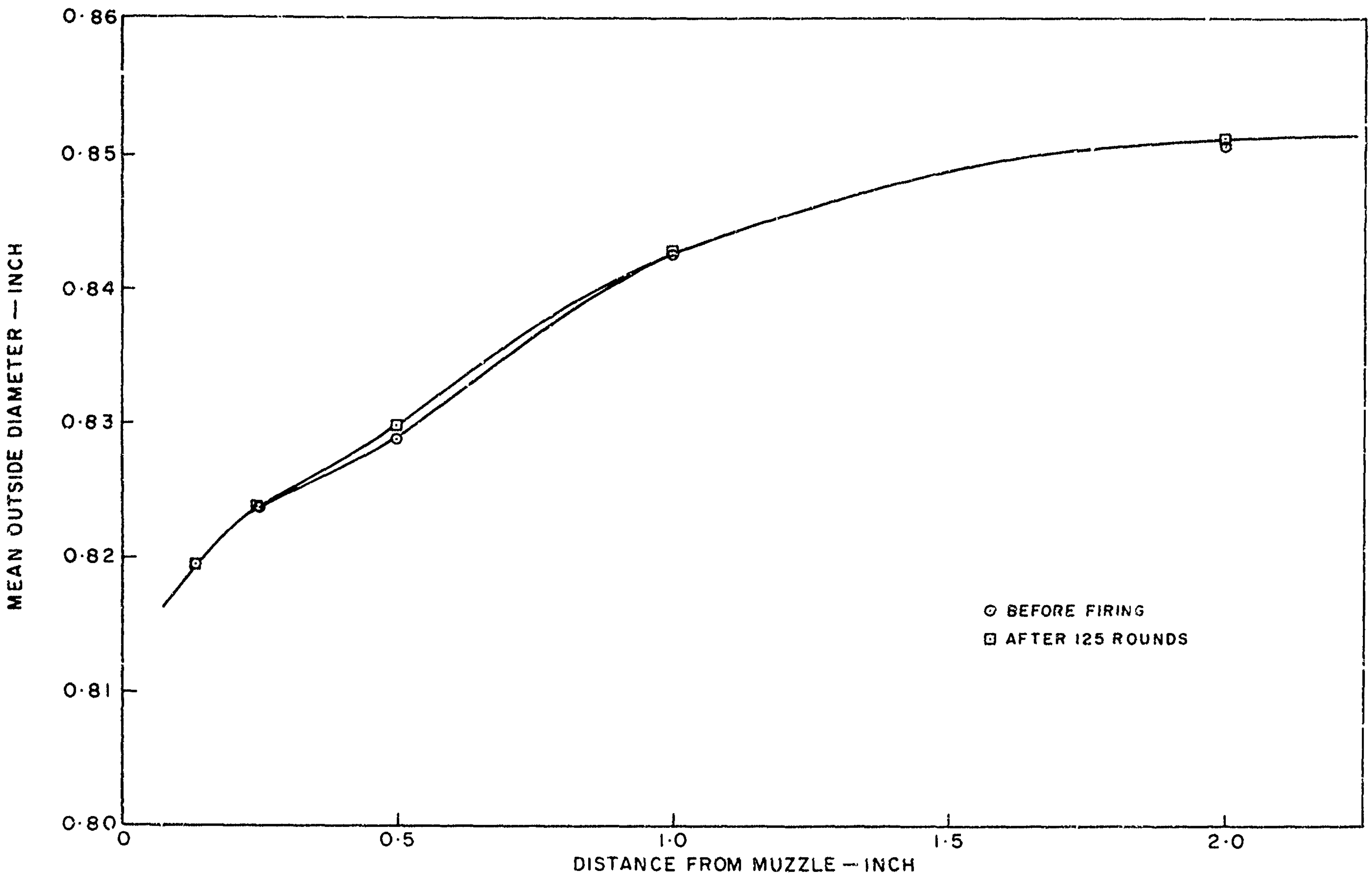


FIG. 10: OUTSIDE DIAMETER AT MUZZLE, LEAD SHOT

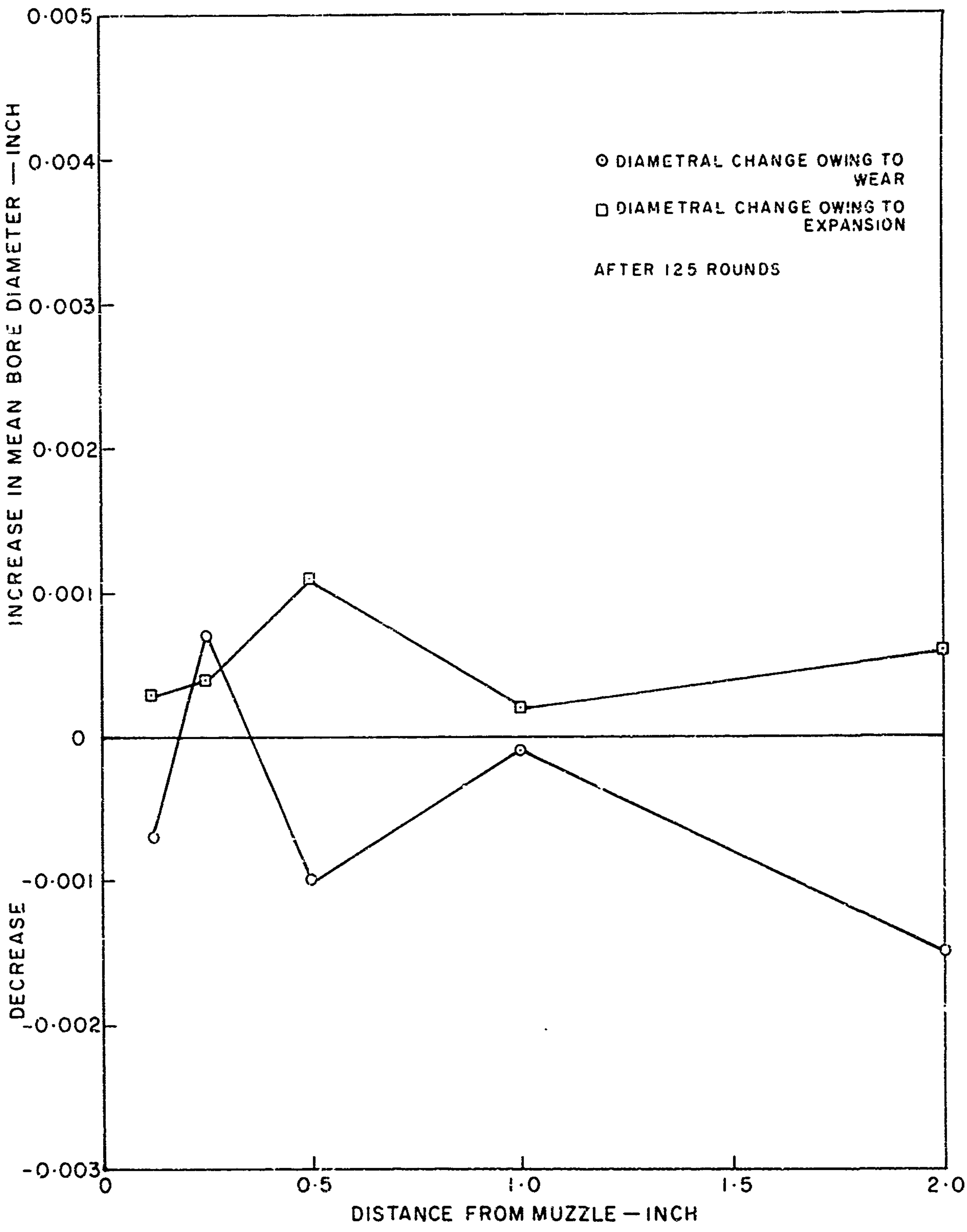


FIG. 11: CHANGES IN BORE DIAMETER OWING TO WEAR AND EXPANSION, LEAD SHOT

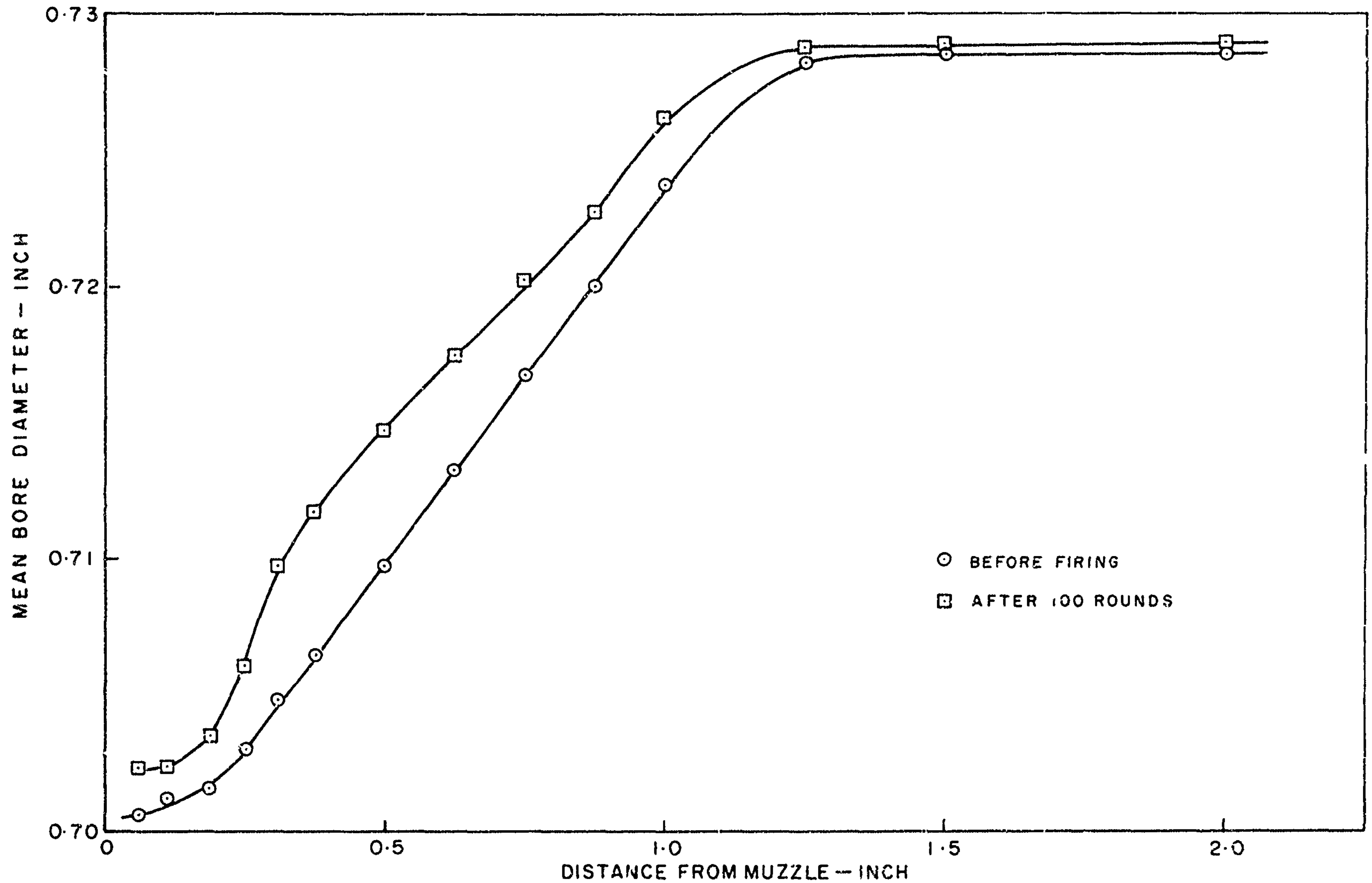


FIG.12: BORE DIAMETER AT MUZZLE, CARBONYL NICKEL SHOT

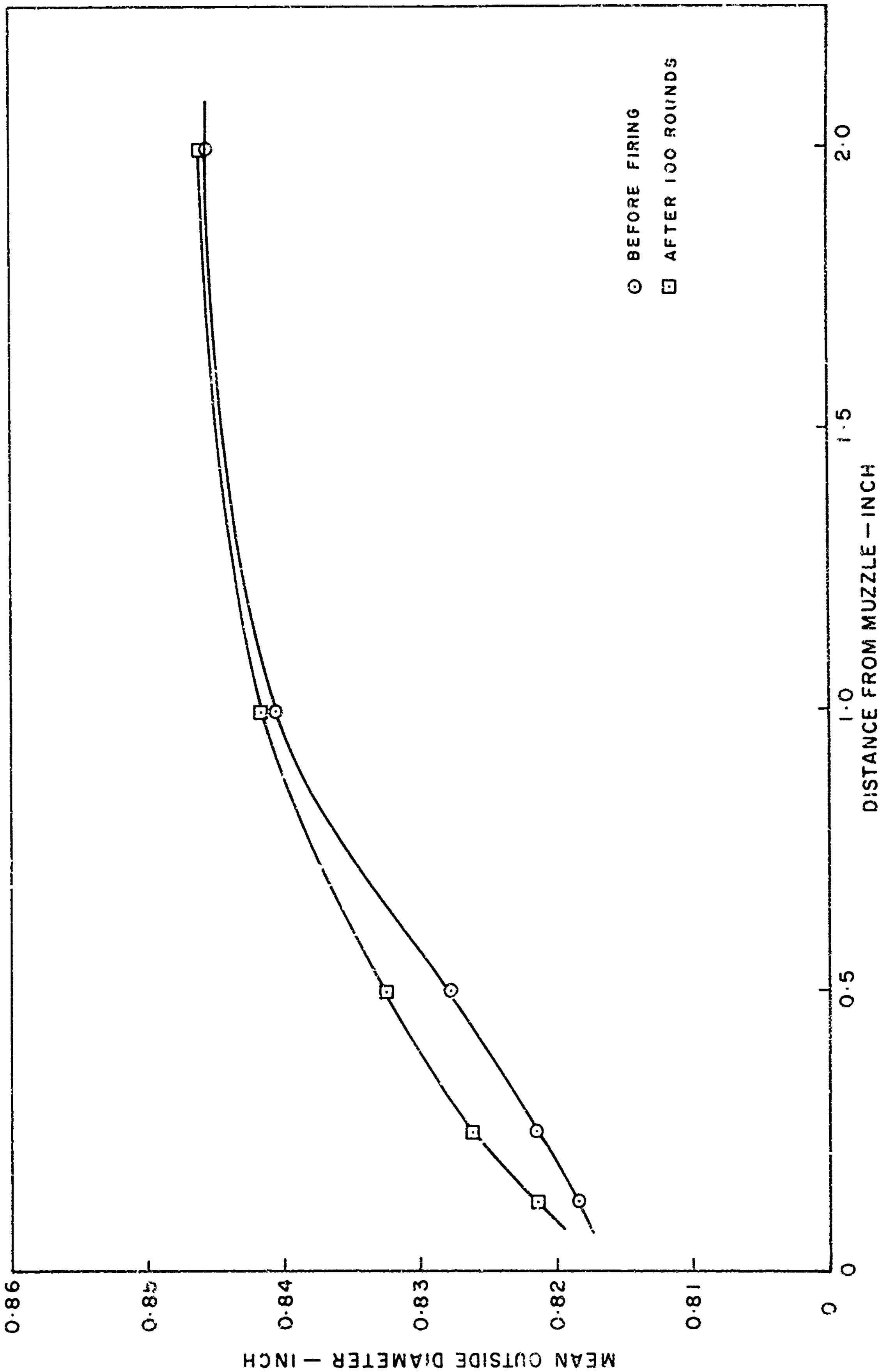


FIG. 13: OUTSIDE DIAMETER AT MUZZLE, CARBONYL NICKEL

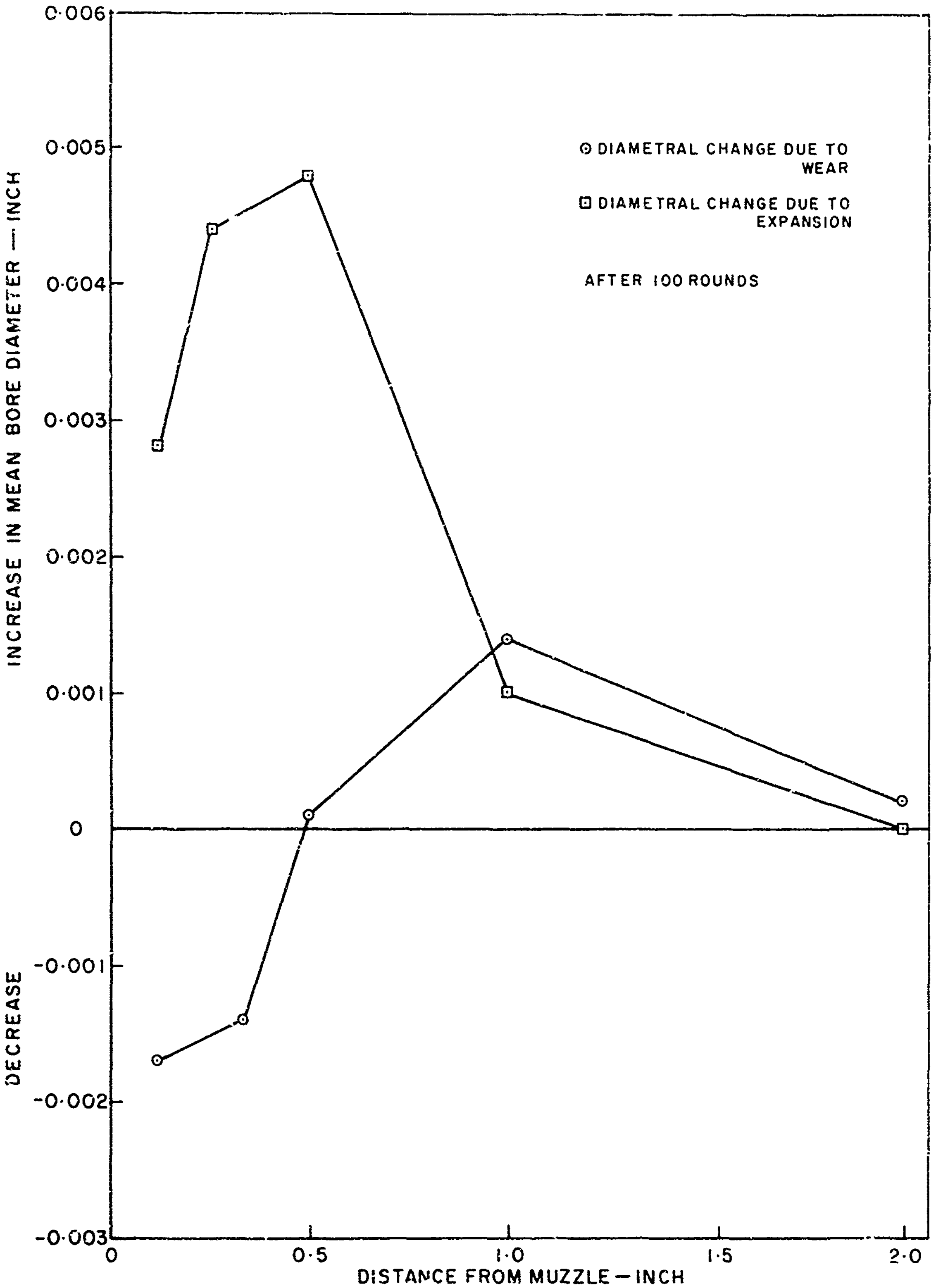


FIG. 14: CHANGES IN BORE DIAMETER OWING TO WEAR AND EXPANSION, CARBONYL NICKEL SHOT

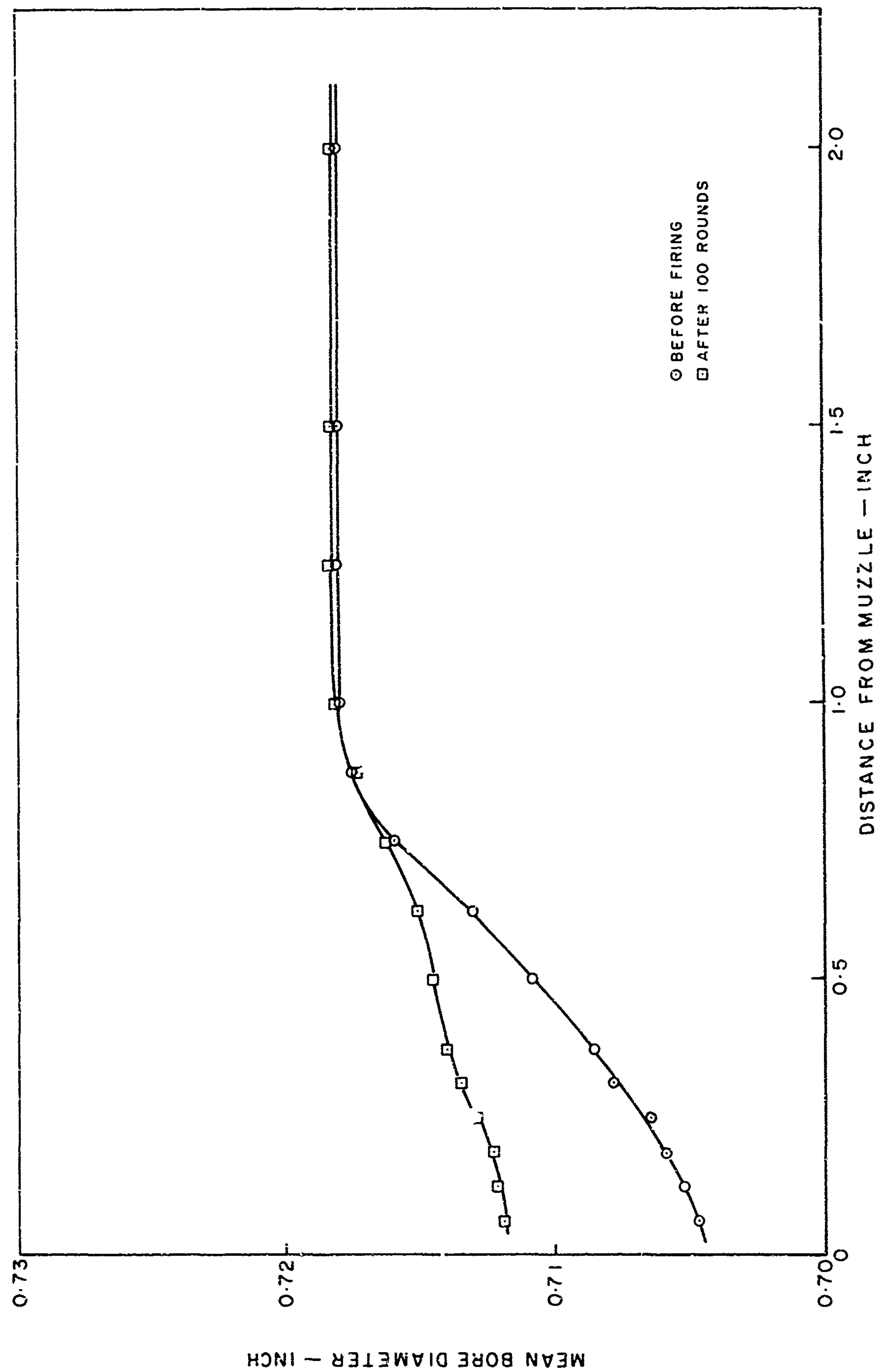


FIG. 15: BORE DIAMETER AT MUZZLE, STEEL BB SHOT

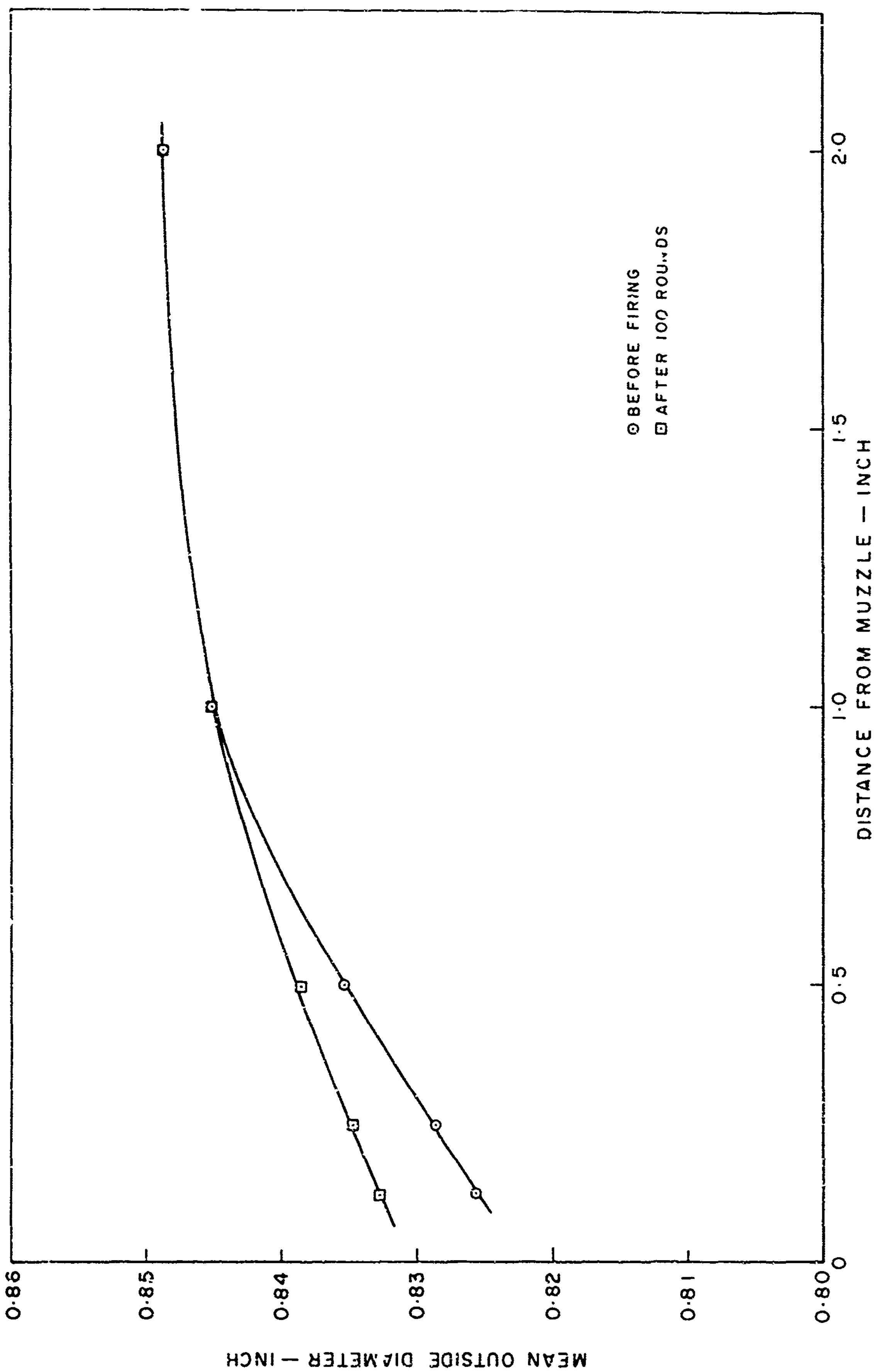


FIG 16: OUTSIDE DIAMETER AT MUZZLE, STEEL BB SHOT

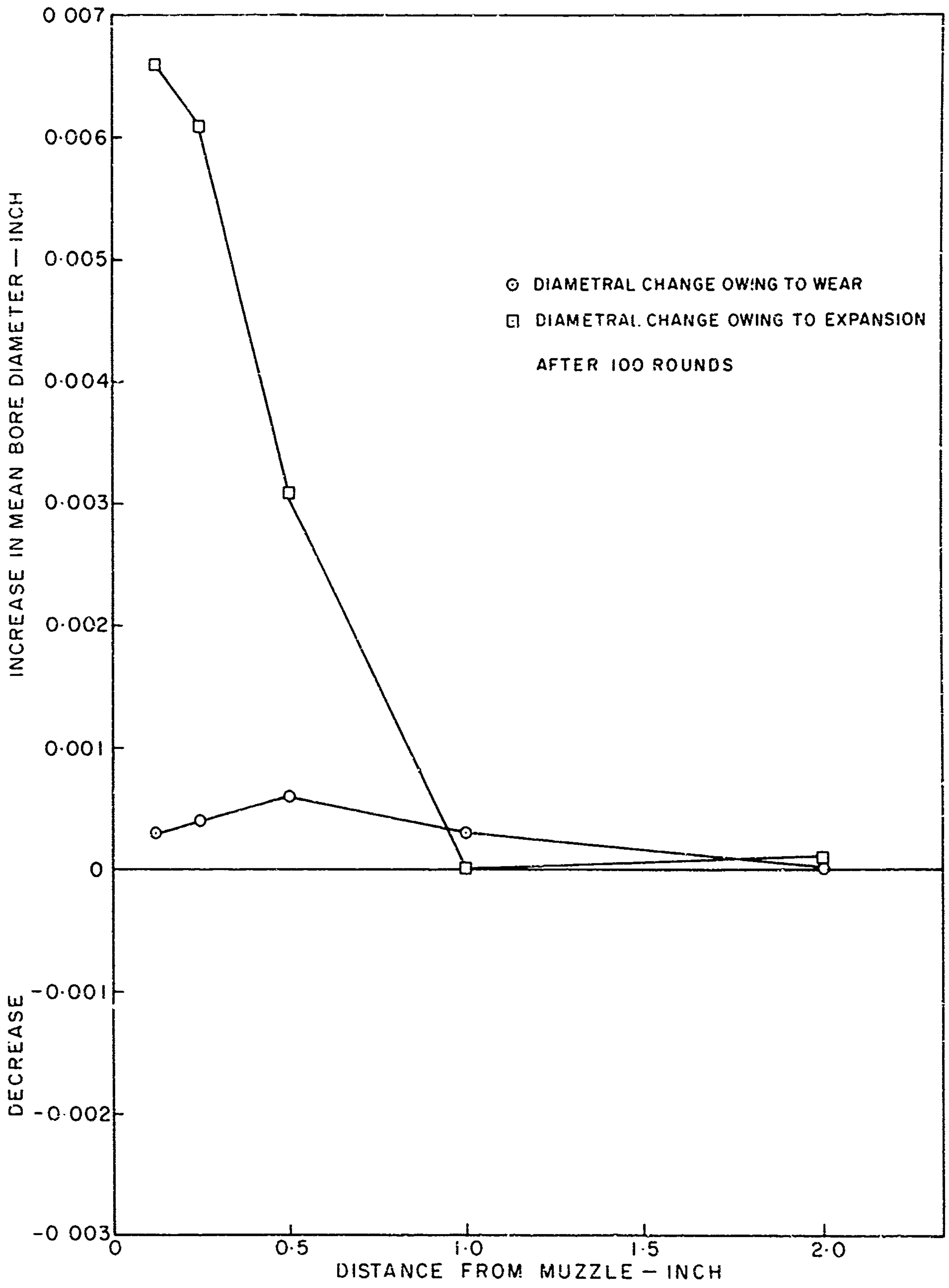


FIG.17: CHANGES IN BORE DIAMETER OWING TO WEAR AND EXPANSION, STEEL BB SHOT

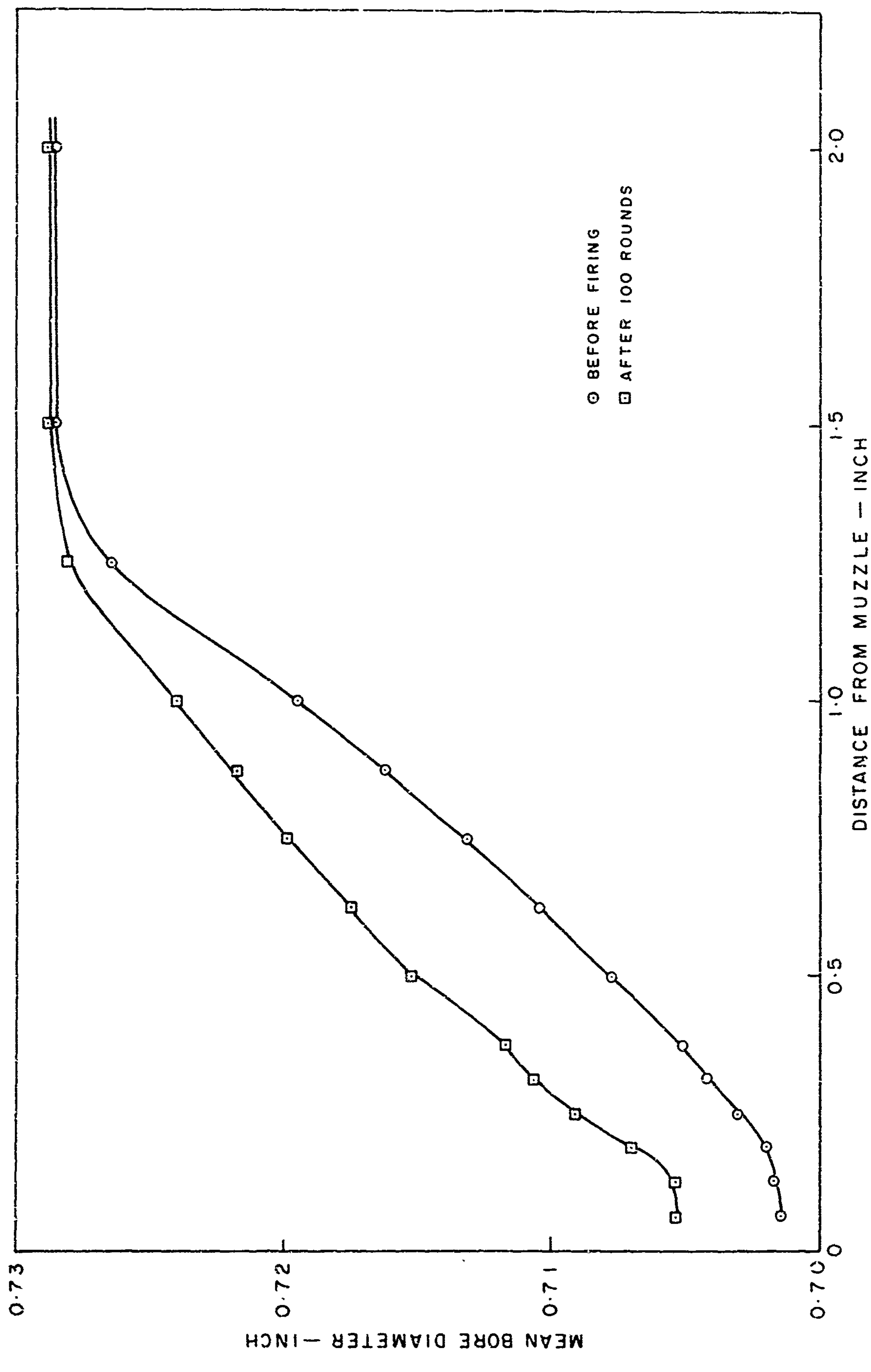


FIG.18: BORE DIAMETER AT MUZZLE, EPOXY RESIN COATED NICKEL

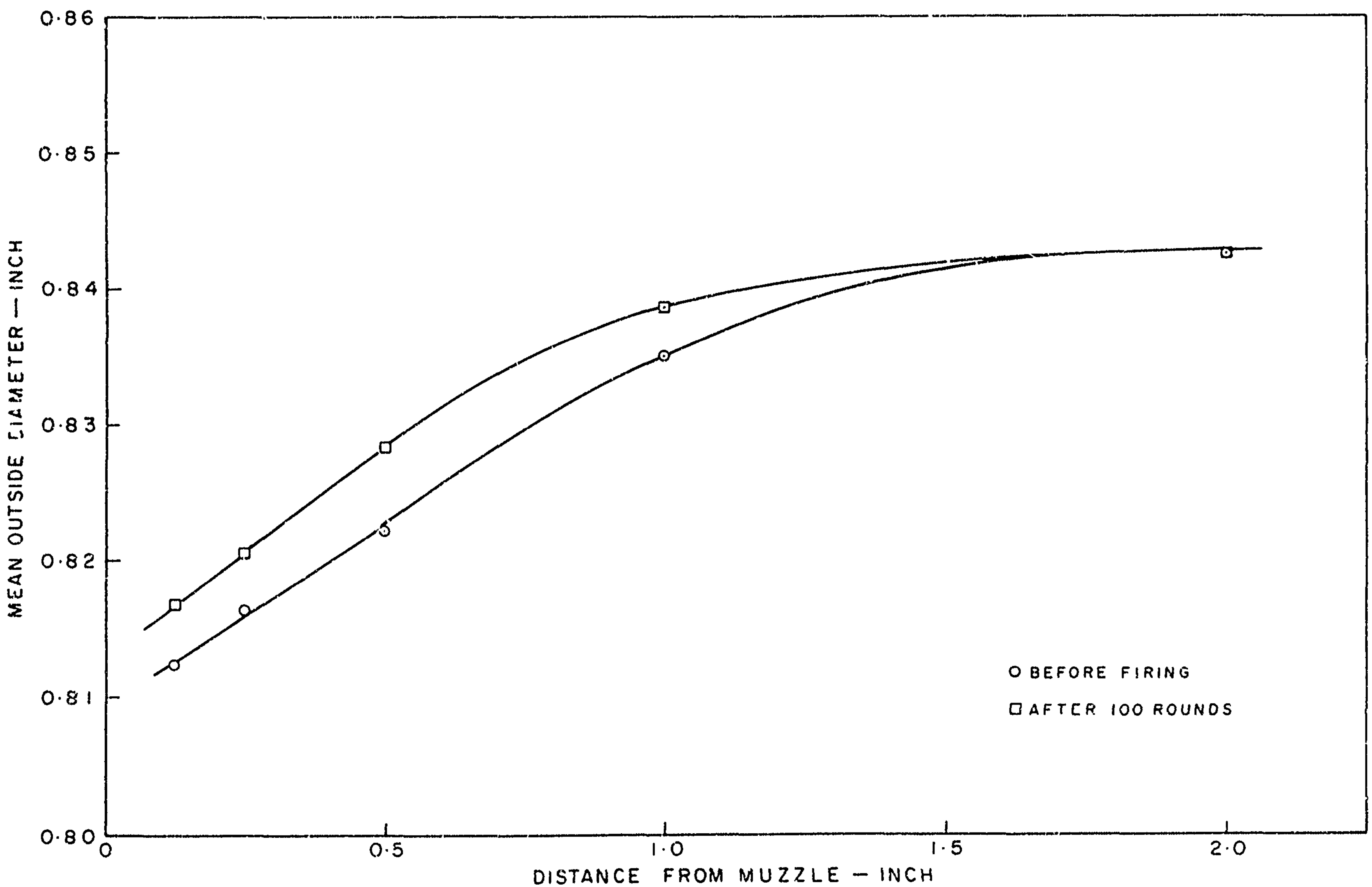


FIG. 19: OUTSIDE DIAMETER AT MUZZLE, EPOXY RESIN COATED NICKEL

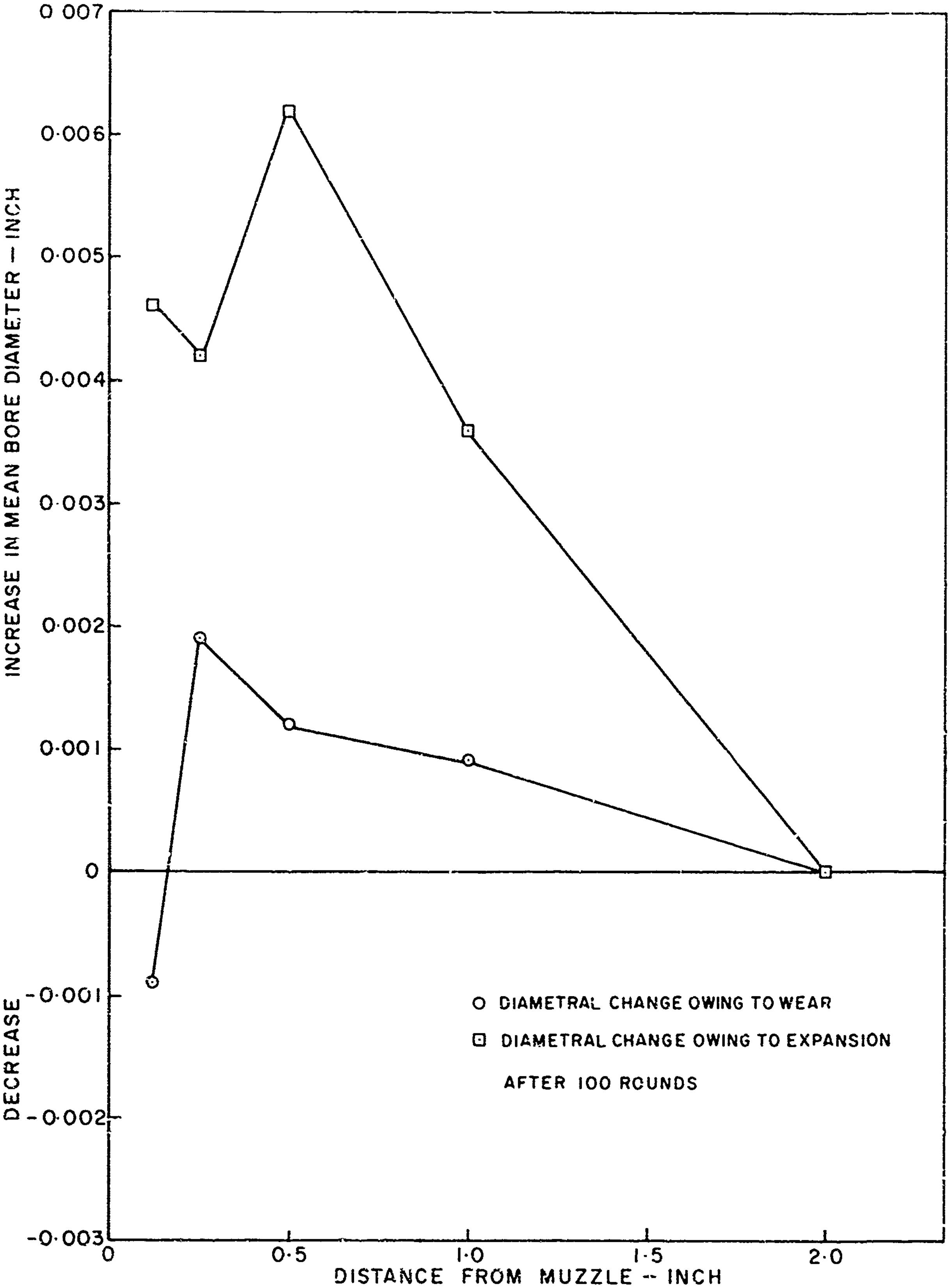


FIG.20: CHANGES IN BORE DIAMETER OWING TO WEAR AND EXPANSION, EPOXY RESIN COATED N CKEL SHOT

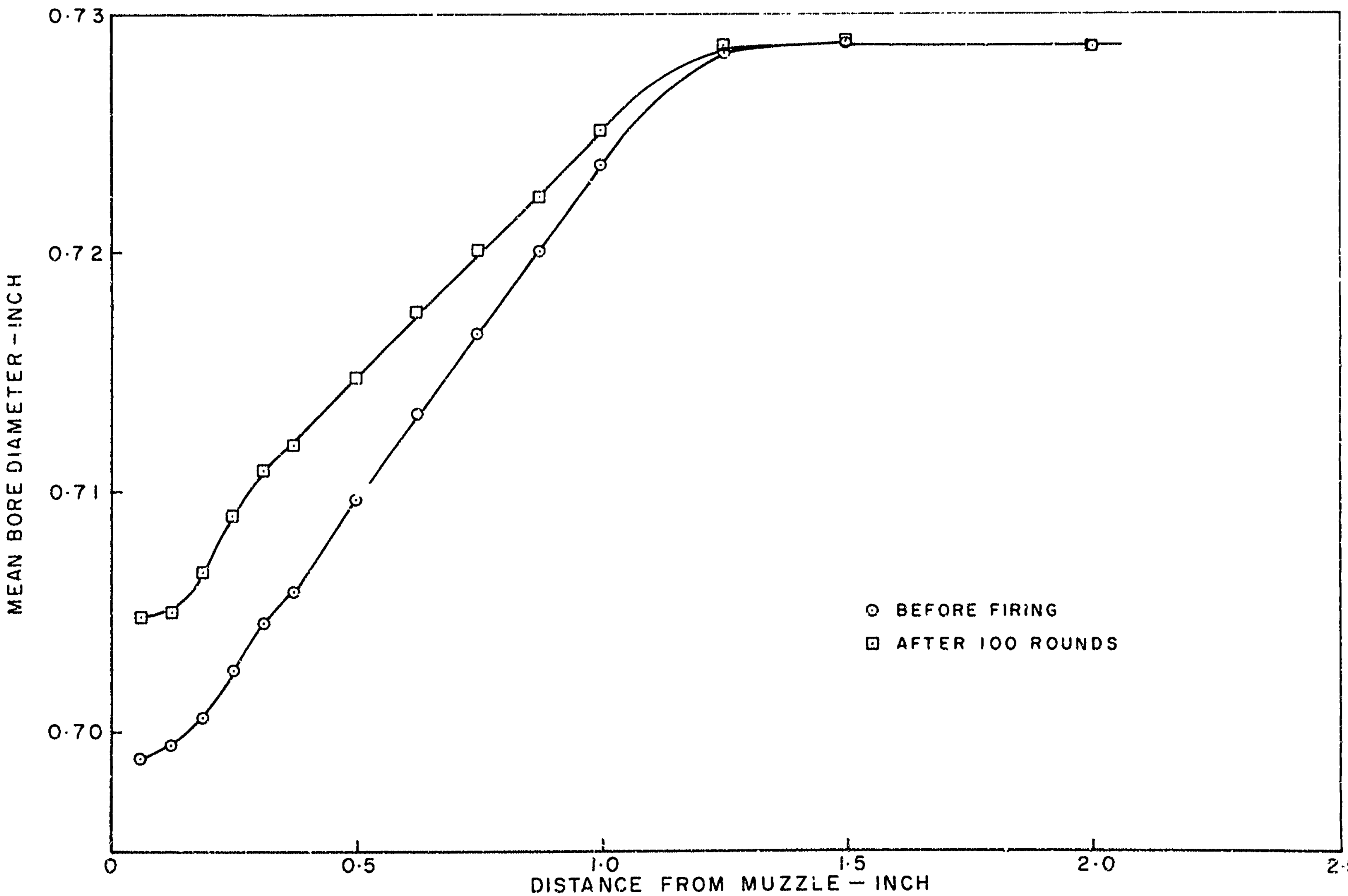


FIG.21: BORE DIAMETER AT MUZZLE, NICKEL SHOT BURNISHED WITH MoS_2 POWDER

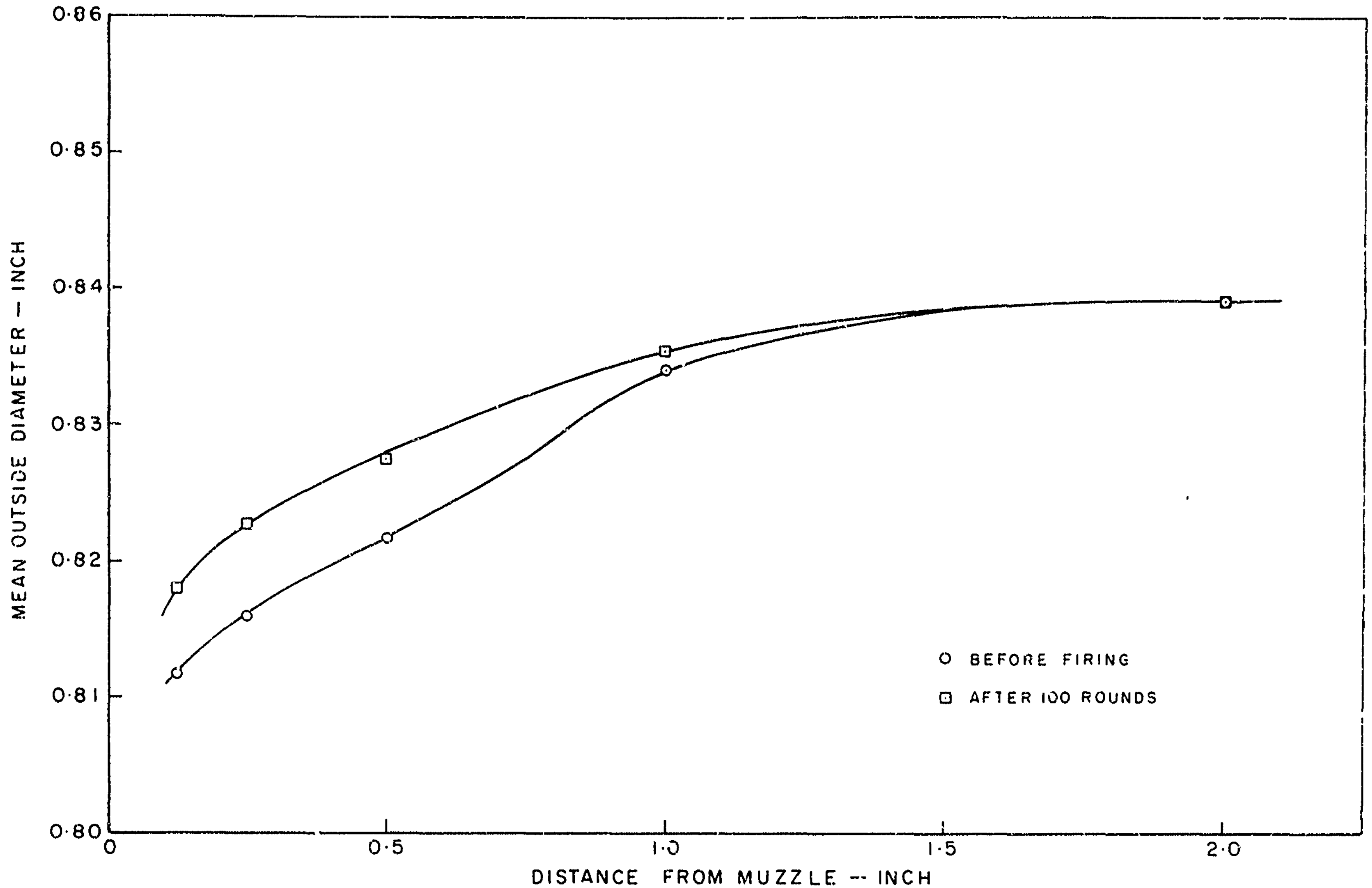


FIG.22: OUTSIDE DIAMETER AT MUZZLE, NICKEL SHOT BURNISHED WITH MoS_2 POWDER

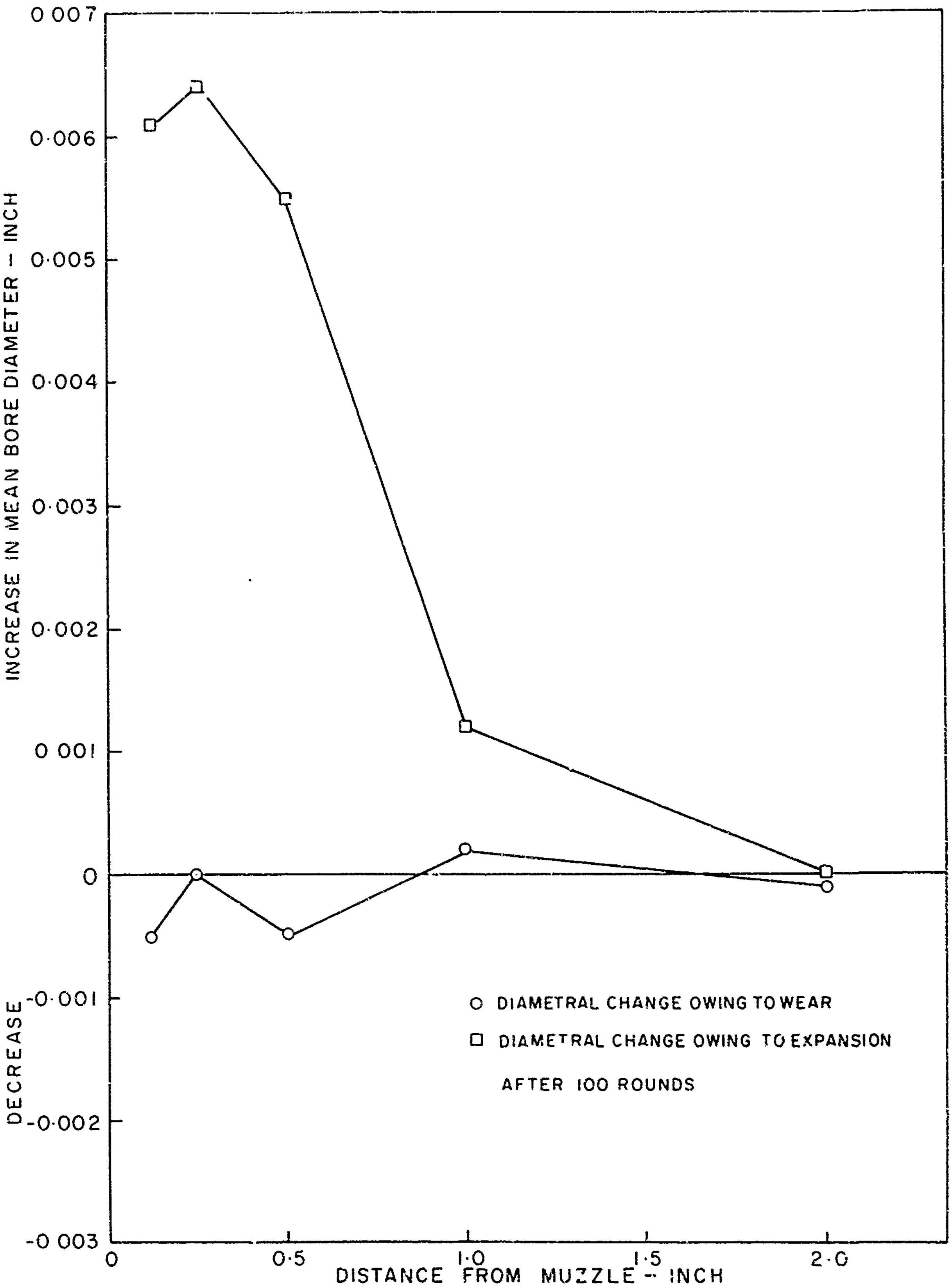


FIG.23: CHANGES IN BORE DIAMETER OWING TO WEAR AND EXPANSION, NICKEL SHOT BURNISHED WITH MoS_2 POWER

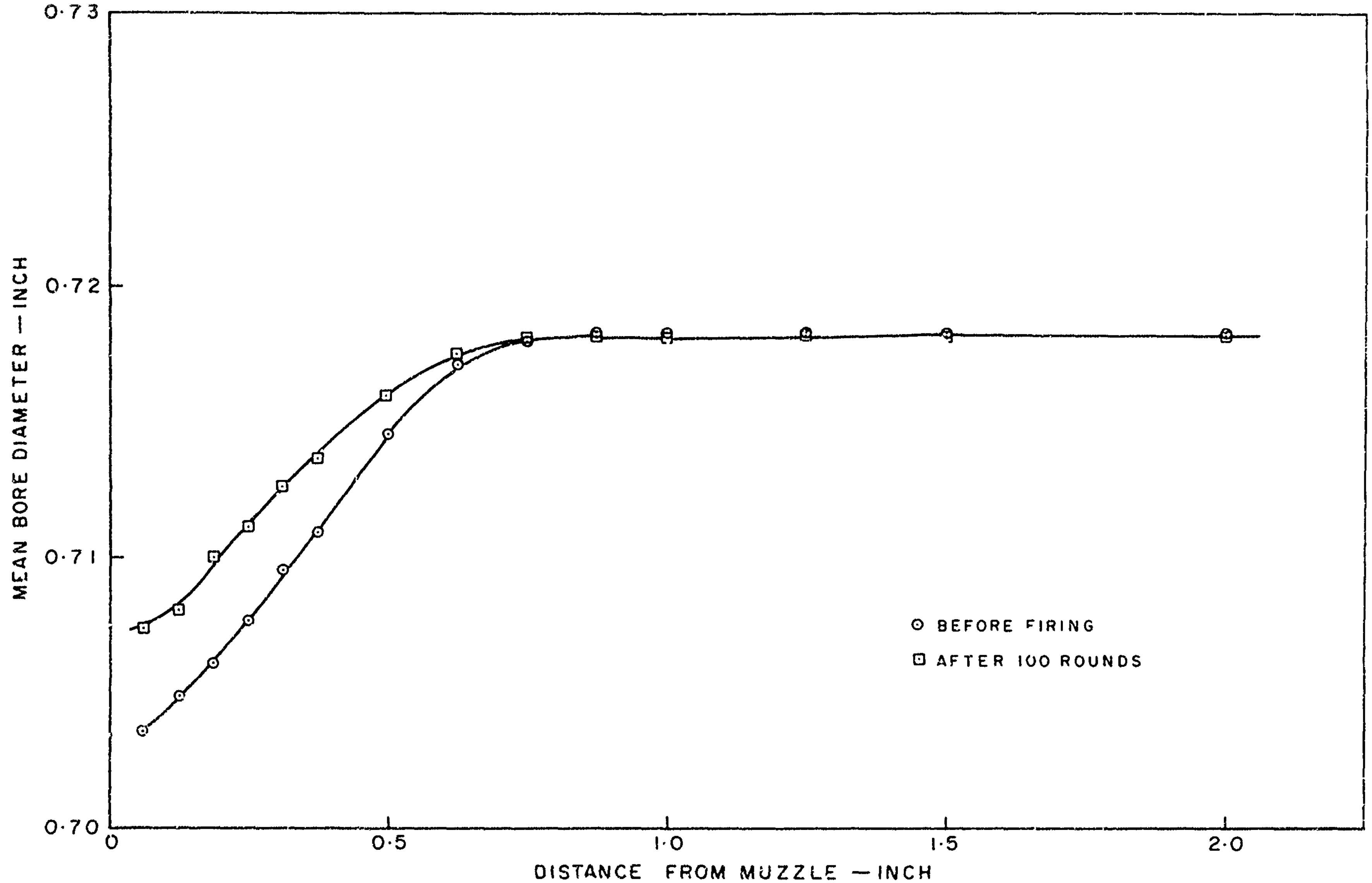


FIG.24: BORE DIAMETER AT MUZZLE, NICKEL SHOT COATED WITH RESIN BONDED MoS_2

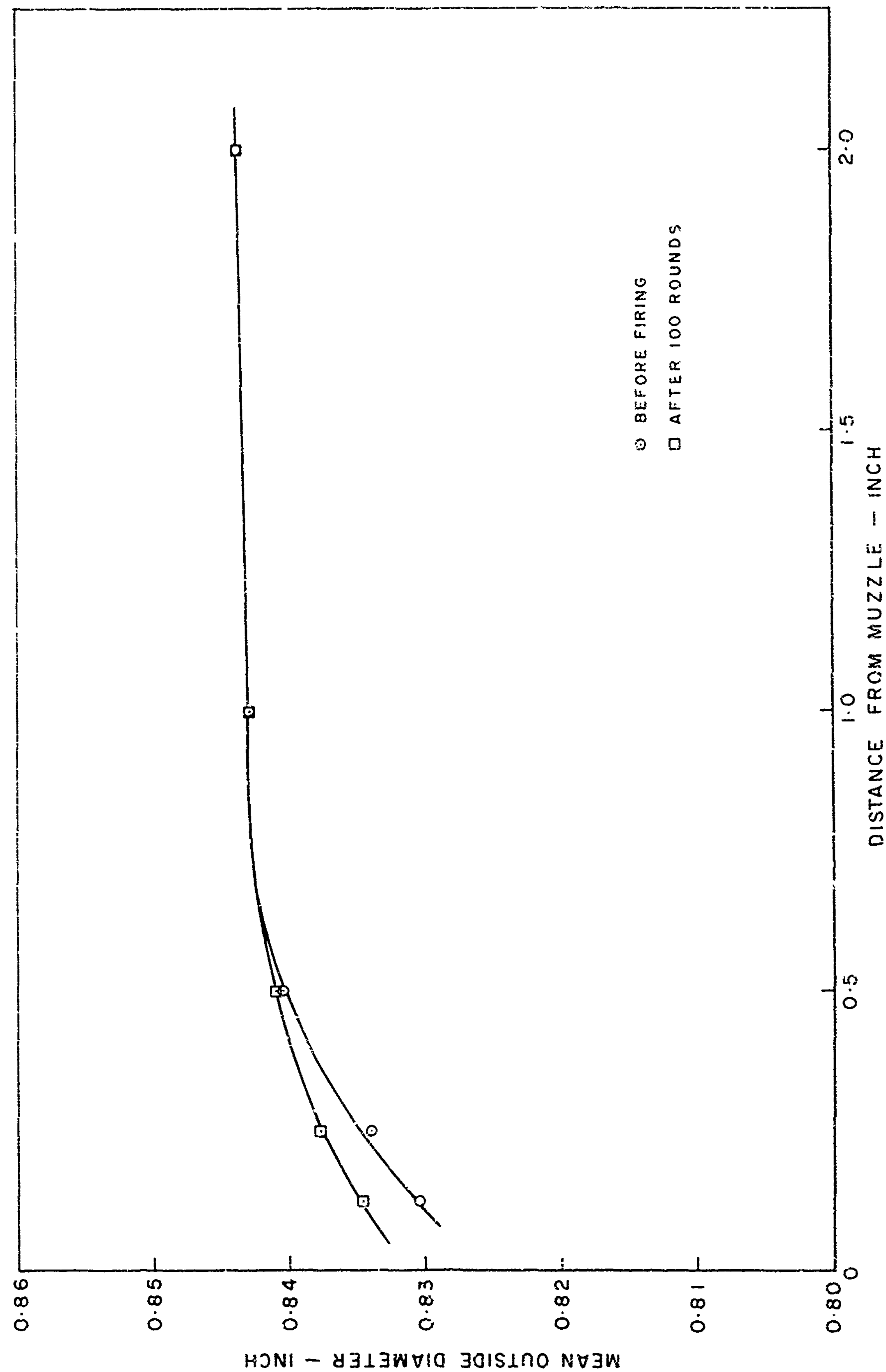


FIG. 25: OUTSIDE DIAMETER AT MUZZLE, NICKEL SHOT COATED WITH RESIN BONDED MoS_2

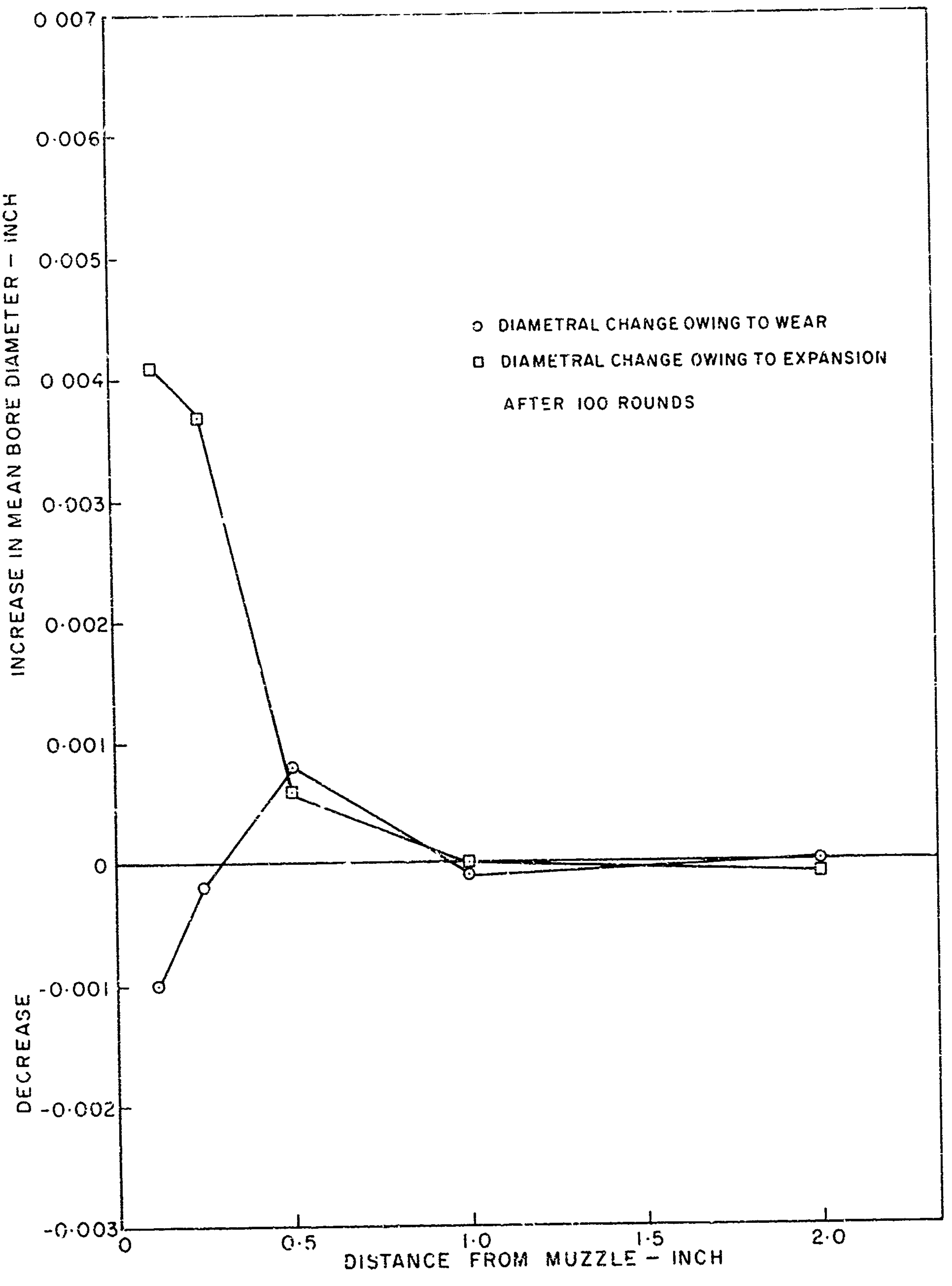


FIG.26: CHANGES IN BORE DIAMETER OWING TO WEAR AND EXPANSION, NICKEL SHOT COATED WITH RESIN BONDED MoS_2

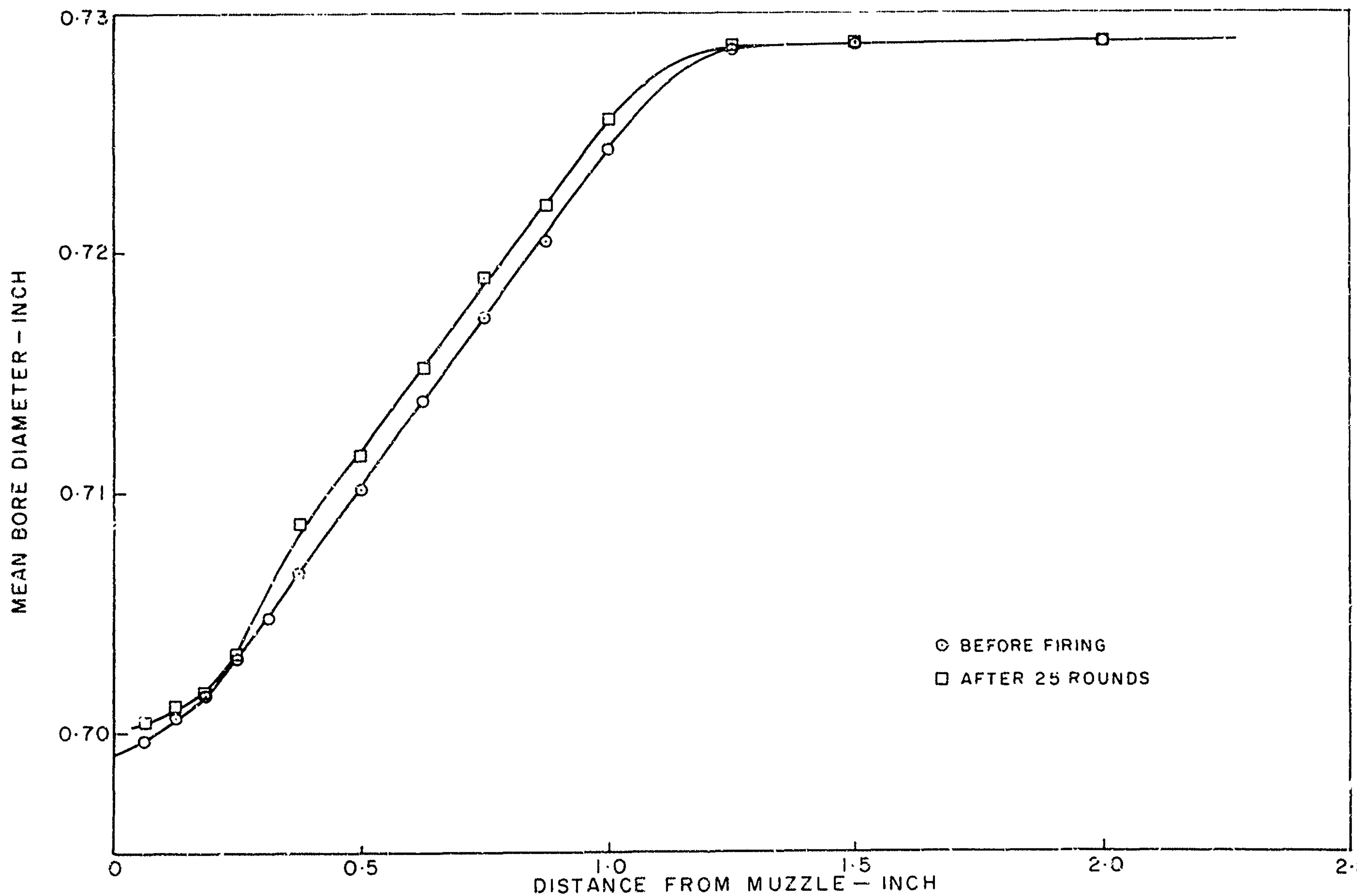


FIG.27: BORE DIAMETER AT MUZZLE, TEFLON COATED NICKEL SHOT

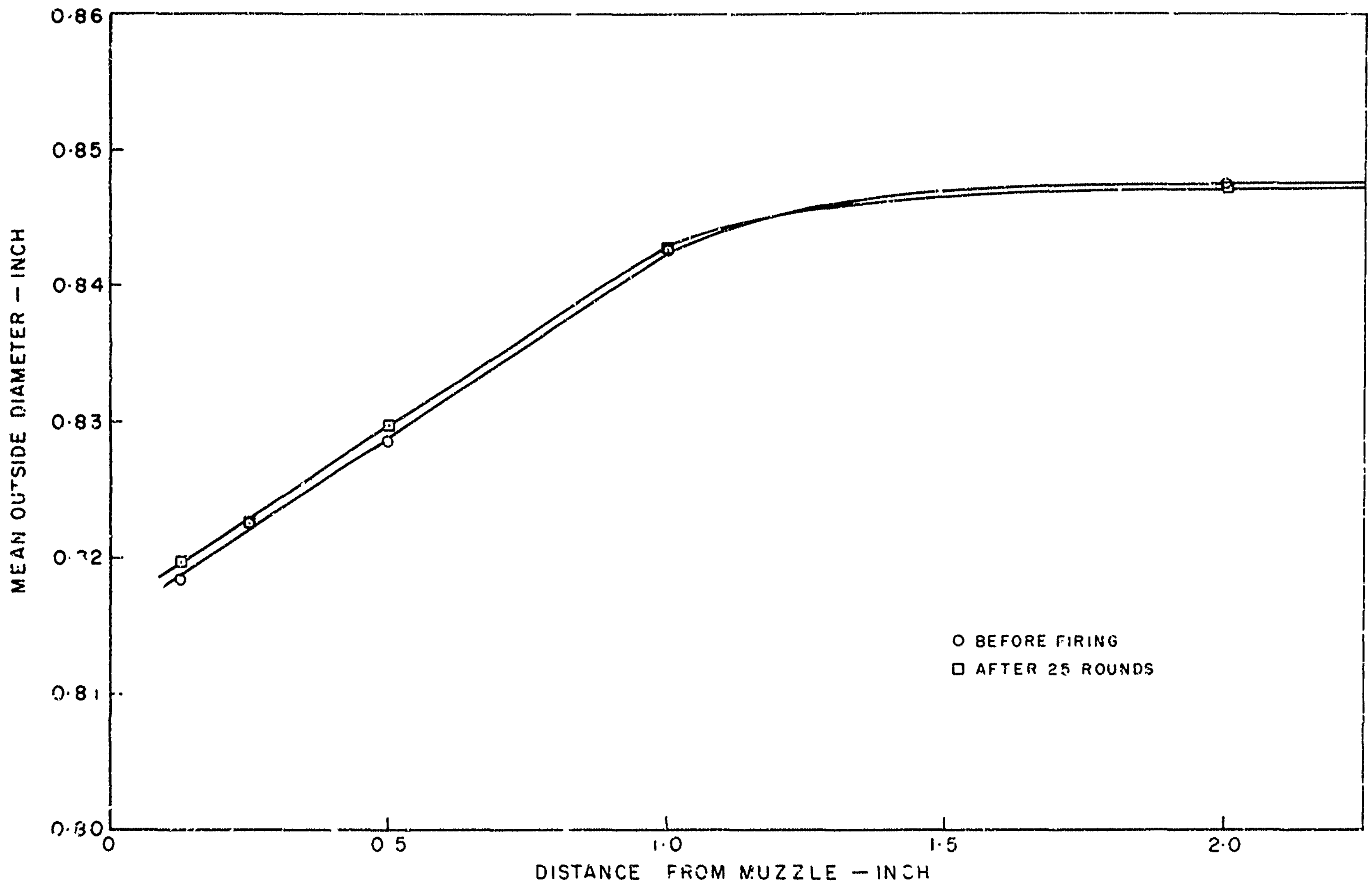


FIG. 28: OUTSIDE DIAMETER AT MUZZLE, TEFLON COATED NICKEL SHOT

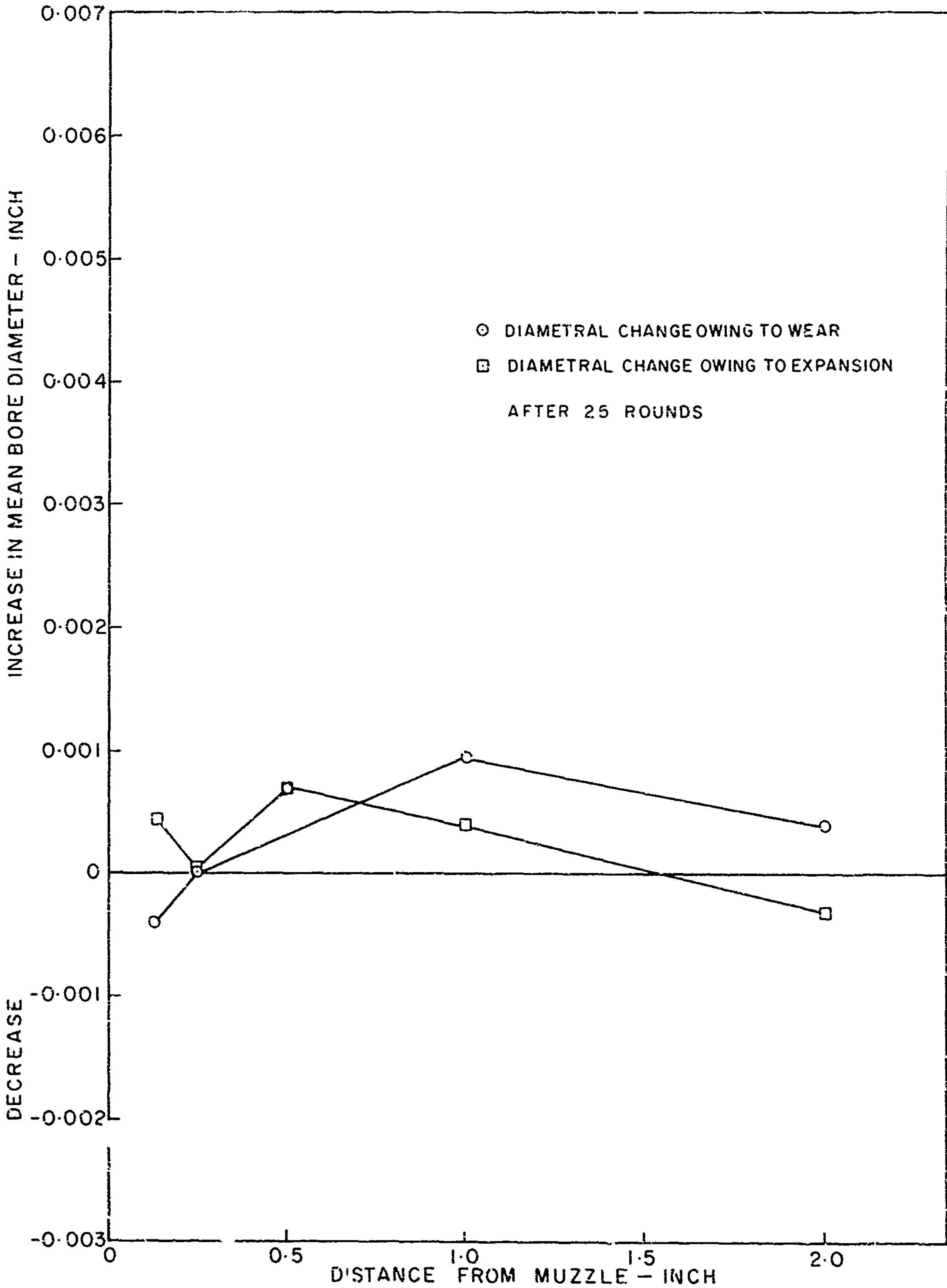


FIG.29: CHANGES IN BORE DIAMETER OWING TO WEAR AND EXPANSION, TEFLON COATED NICKEL SHOT

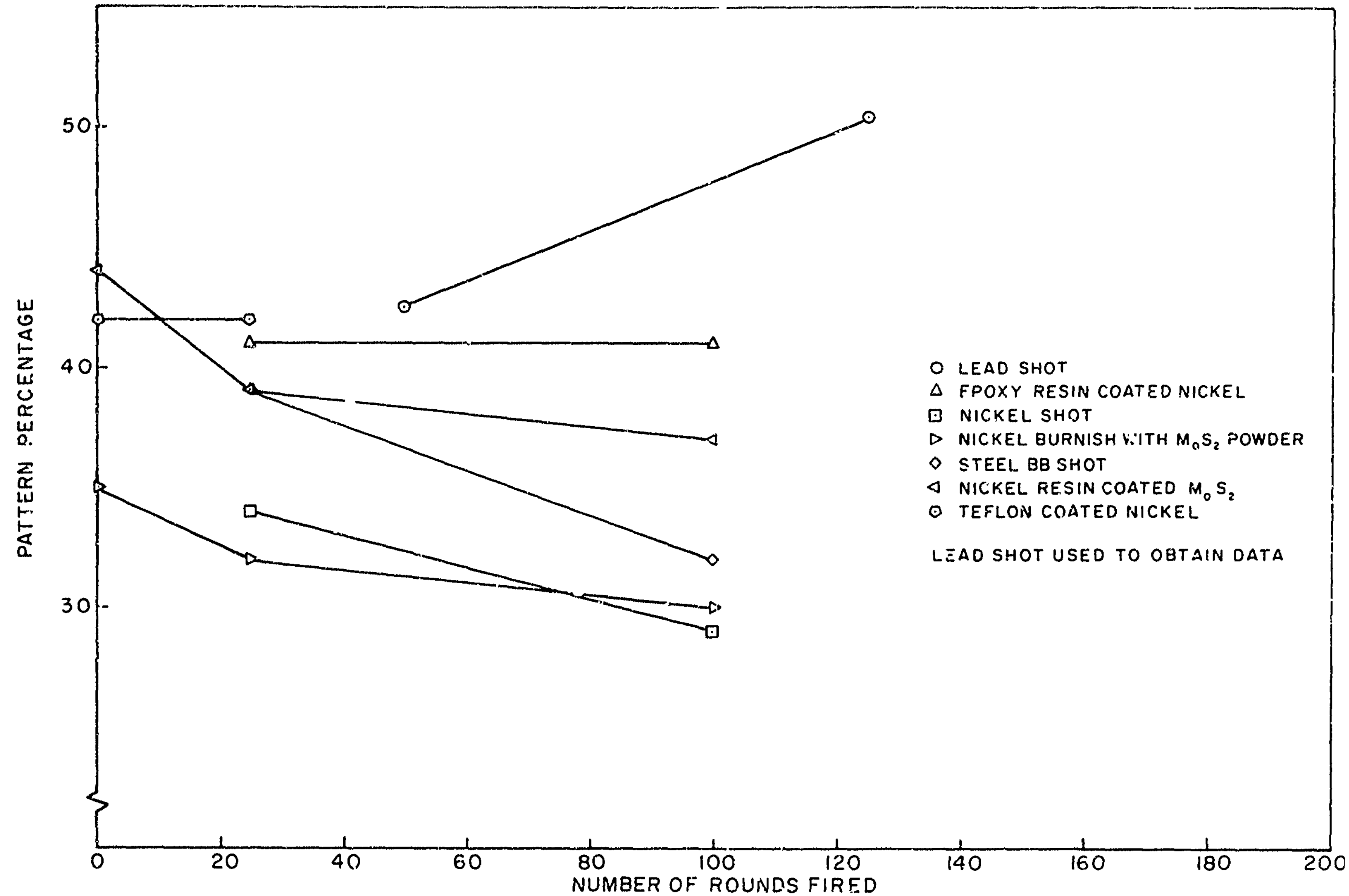
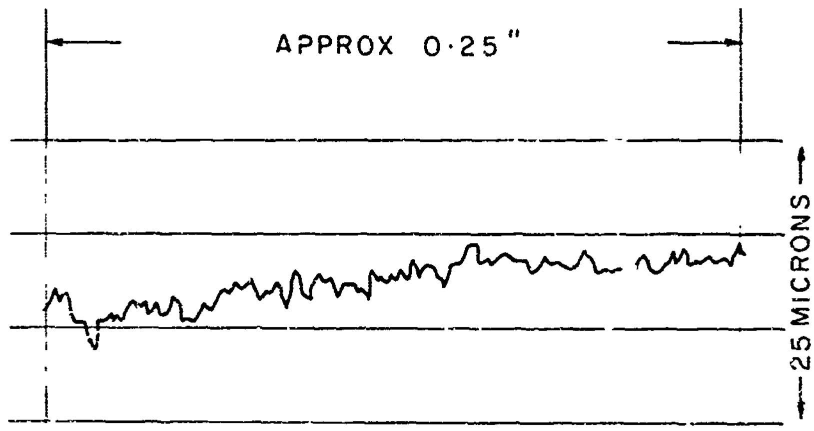
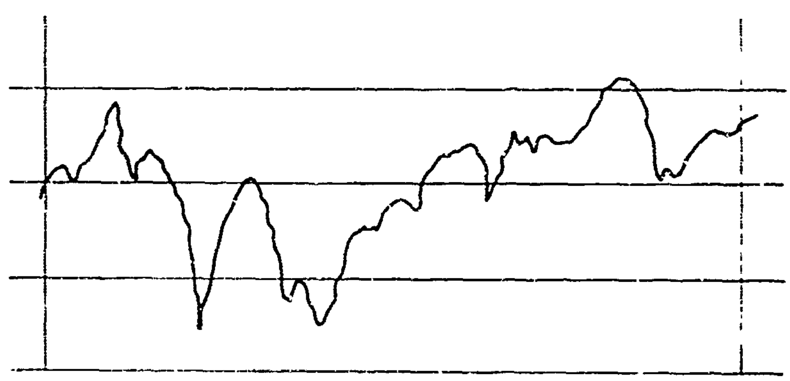


FIG 30: AVERAGE PATTERN PERCENTAGE AS A FUNCTION OF NUMBER OF ROUNDS FIRED



BEFORE FIRING
CENTRE LINE AVG 48–52 μ IN



AFTER 100 ROUNDS
CENTRE LINE AVG 110–115 μ IN

FIG. 31: TALYSURF TRACE BEFORE AND AFTER 100 ROUNDS
CARBONYL NICKEL

FIG.32: BARREL BORE AT MUZZLE OF UNUSED GUN

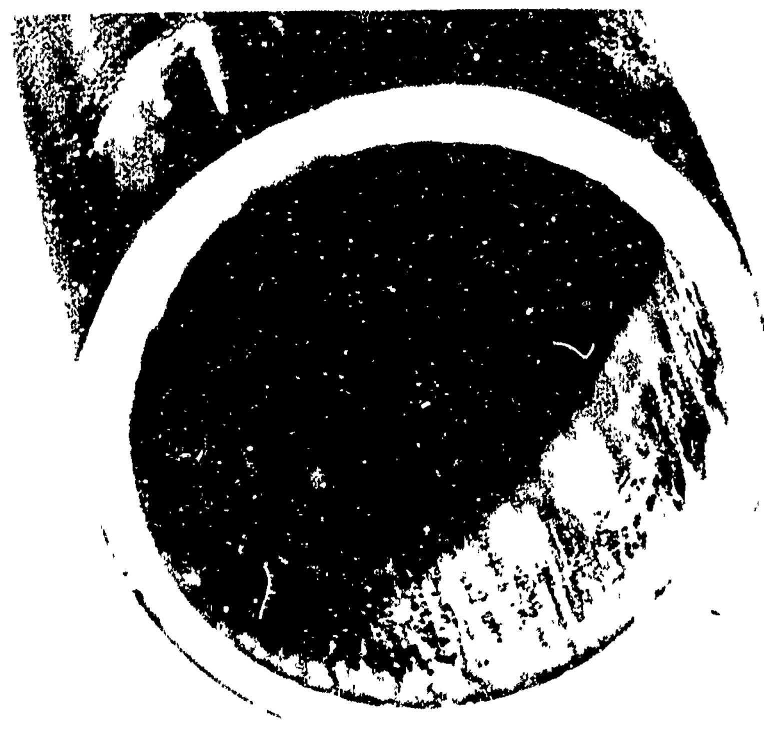


FIG. 33: BARREL BORE AT MUZZLE OF GUN FROM WHICH TWENTY-FIVE ROUNDS OF CARBONYL NICKEL WAS FIRED